Energy Efficient Multi-story Residential Buildings in China

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Abstract

Energy efficient multi-story residential building is a common approach in China. Demonstration buildings are built in recent years for research purpose. Energy efficiency in such buildings is excellent. However, these demonstration buildings are much more like a collage of modern technology. For clients, it is important to know which strategy is the most suitable for certain building, considering the investment, life-cycle cost and special climate condition.

In this research, energy efficient strategies are discussed and compared under different climate conditions. Primary energy demand and total cost in service life are two indexes. Based on these, suggestions about energy efficient multi-story building design will be convincing.

The main part of this research has two main aspects, which are building envelope and building heating and cooling technology. Five cities (Urumqi, Beijing, Shanghai, Guangzhou, Kunming) are chosen as representative cities in these climate zones (severe cold, cold, hot summer and cold winter, hot summer and warm winter, warm). A typical Chinese multi-story residential building with detailed design of the building envelope (depending on the city) is built in software “DesignBuilder” as basic model. Common heating and cooling systems are taken as reference systems.

In the first parameter study, insulation layers of external wall, glazing types, window-to-wall ratio are discussed under selected climate conditions. The simulation program “DesignBuilder” is used to calculate the useful energy demand.

In the second parameter study, overall building service system including space heating, space cooling, domestic hot water, lighting and appliances is examined. Different building service technologies such as solar thermal system, ground-coupled heat pump, air-source heat pump and photovoltaic system are discussed. Primary energy demand and total cost in service life are compared among different combinations. Simulation programs “Trnsys” and “PV*SOL” are used.

As results of this research, optimal thickness of insulation layers, optimal window-to-wall ratio and glazing types are shown for five climate conditions. Optimal thicknesses of EPS for external wall are approximate 200mm in Urumqi, Beijing and Shanghai. Double Low-E glazing (D-LOE) is the most suitable glazing type in cold cities (Urumqi and Beijing), while double reflect glazing (D-REF) is the best choice in hot cities (Guangzhou) and warm cities (Kunming). High WWR (50% up to 90%) is more suitable for southern windows in cold cities (Urumqi and Beijing), while small WWR (20% up to 40%) is better for northern windows; In Guangzhou and Kunming, where cooling demand is dominant, small WWR (20% up to 40%) is suggested for both northern and southern windows; In Shanghai, which locates in hot summer and cold winter zone, large window (WWR 50% up to 90%) with integrated shading system should be considered.

Using solar thermal system for domestic hot water and space heating could reduce the primary energy

demand 13% up to 25%. Compared with other advanced systems (system-A,B,C), the combination of GCHP and PV (system-D) could achieve the lowest primary energy demand, which is about 46% up to 53% lower than the reference system. With government financial support for PV technology, it could achieve the lowest total cost on service life (20 years). Because of the quickly decreasing module price, PV system will be more competitive in the future. The combination of GCHP and PV is supposed to be the most suitable solution for energy supply in Chinese multi-story residential building in the near future.

Kurzfassung

Das Bewusstsein des energieeffizienten Bauens von Mehrfamilienhäusern wird in China immer populärer. Zu Forschungszwecken sind in den letzten Jahren einige Pilotprojekte verwirklicht worden. Der energetische Anspruch an solch Häuser ist zwar hoch, dennoch sind diese Gebäude meist nur eine Ansammlung von moderner Technik statt einer ganzheitliche Systemlösung. Für die Käufer neuer Wohnungen ist es wichtig zu wissen, welche Gebäudestandards sich am besten eignen, um unter der Berücksichtigung spezieller klimatischer Bedingungen und der Lebenszykluskosten, Gebäude nachhaltig zu realisieren und zu betreiben.

In diesem Forschungsprojekt werden energieeffiziente und Kostenoptimale Strategien unter verschiedenen klimatischen Bedingungen für China diskutiert. Der jährlich Primärenergiebedarf und die Lebenszykluskosten sind dafür zwei wesentliche Indizes. Auf dieser Grundlage werden Vorschläge für ein energieeffizientes Gebäude- und Technikdesign bei Mehrfamilienhäusern in China ausgearbeitet.

Die Arbeit untergliedert sich in zwei Bereiche. Neben der Gebäudehülle liegt ein weiterer Schwerpunkt auf der Gebäudetechnik. Dabei werden für fünf Klimazone typische Städte ausgewählt, Urumqi (extrem kalte Zone), Beijing (kalte Zone), Shanghai (heißer Sommer und kalter Winter), Guangzhou (heißer Sommer und milder Winter) and Kunming (milde Zone). Der Entwurf eines typischen chinesischen Mehrfamilienhauses wird mit dem Simulations Programm "DesignBuilder" als Basismodell abgebildet. Bestehenden Gebäudetechnik für Raumheizung, Warmwasser und Raumkühlung werden als Referenzsysteme angenommen.

Im ersten Teil der Parameterstudie werden Dämmschichtstärken, Verglasungsart und -anteil für die fünf klimatischen Bedingungen diskutiert. Das Simulationsprogram "DesignBuilder" wird benutzt um den jährlichen Nutz Energiebedarf zu ermitteln.

Im zweiten Teil der Parameterstudie werde die Gebäudetechnik (einschließlich Raumheizung, Raumkühlung, Warmwasser, Beleuchtung und Haushaltsgeräte) umfassend untersucht. Verschiedene Gebäudetechnologien, wie thermische Solaranlagen, Sole/Wasser- Wärmepumpen, Luft/Wasser-Wärmepumpen und Photovoltaik-Anlagen, werden diskutiert. Der Primärenergiebedarf und die Lebenszyklus Kosten für verschiedene Kombinationen werden verglichen. Dazu werden die Simulationsprograme "TRNSYS" und "PV*SOL" verwendet.

Aus dieser Untersuchung werden die optimale Dämmstoffstärke, der optimale Verglasungsanteil und die Verglasungsart für die fünf klimatischen Zonen aufgezeigt. In Urumqi, Beijing and Shanghai, optimale Dicken von EPS für Außenwand sind ca. 200 mm. Doppel Wärmeschutzverglasung (D-LOE) ist die am besten geeignete Verglasung in kalten Städten (Urumqi und Bejing). Doppel Sonnenschutzverglasung (D-REF) ist die beste Wahl in heissen Städten (Guangzhou) und warm Städten (Kunming) . In kalten Städten (Urumqi und Beijing) soll der Fensterflächenanteil für Süd-Fenster groß (50% bis 90%) und für

Nord-Fenster klein (20% bis 40%) sein. In Guangzhou und Kunming, wo Kühlbedarf dominant ist, wird der Fensterflächenanteil mit 20% bis 40% vorgeschlagen. In Shanghai, der sich in der Zone "heißer Sommer und kalter Winter" befindet, sollte große Fenster (Fensterflächenanteil 50% bis 90%) mit integriertem Sonnenschutz berücksichtigt werden.

Durch den Einsatz einer Solaranlage zu Unterstützung der Warmwasserbereitung und Raumheizung können 13% bis 25% Primärenergie eingespart werden. Noch größere Einsparung an Primärenergie (46% bis 53%) lässt sich durch die Kombination von Sole/Wasser Wärmepumpen und PV-Anlagen erreichen. Durch die relativ hohen staatlichen Förderungen für PV Systems weist die Kombination von Sole/Wassser Wärmepumpe und Photovoltaik Anlagen die niedrigsten Lebenszykluskosten (20a). PV-Systeme werden aufgrund des schnell abnehmenden PV-Modul Preises wettbewerbsfähig im Vergleich zu Strom aus konventionelle Kraftwerk in Zukunft. Die Kombination von Sole/Wasser Wärmepumpen und PV-Anlagen erweist sich als die am besten geeigneteste Lösung für die Energieversorgung in chinesischen mehrgeschossigen Wohngebäuden der Zukunft.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ANF	Factor of Annuity
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCHP	Building combined heating and power system
BIPV	Building-Integrated Photovoltaic System
BMVBS	Bundesministerium für Verkehr, Bau- und Stadtentwicklung
BRE	Building Research Establishment
BREEAM	BRE Environment Assessment Method
CDD	Cooling Degree-Days
CHP	Combined Heat and Power Generation
CMV	Controlled mechanical ventilation system
CoP	Coefficient of Performance
DENA	Deutsche Energie-Agentur
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DHW	Domestic Hot Water
ENEV	Energieeinsparverordnung
EPC	Energy Performance Certificates
EPS	Expanded polystyrene
EURL	Energy Utilization Reasonability Law
GCHP	Ground-Coupled Heat Pump
GHE	Ground-heat-exchanger
HDD	Heating Degree-Days
HERS	Home Energy Rating System
Hips	Home Information Packs
HVAC	Heating, Ventilation and Air Conditioning
IWEC	International Weather for Energy Calculations
LEED	Leadership in Energy & Environmental Design
MLIT	Ministry of Land, Infrastructure and Transport
NatHERS	Nationwide House Energy Rating Scheme
PCM	Phase-change materials
PE	Primary energy factor
PH	PassivHaus
PMV	Predict Mean Vote
PV	Photovoltaic
RESNET	Residential Energy Services Network
RH	Relative Humidity
SC	Space Cooling
SH	Space Heating
SPF	Seasonal performance factor
WSVO	Wärmeschutzverordnung
WWR	Window-to-Wall Ratio

XPS	Extruded Polystyrene

List of Nomenclature

A_{wall}	area of insulated wall [m^2]
A_{window}	area of windows [m^2]
ANF	proportion of annuity [%]
C_{fc}	cooling fuel price [€/kWh]
C_{fh}	heating fuel price [€/kWh]
$C_{insulation}$	cost of thermal insulation [€]
C_L	labor cost [€]
C_M	price of insulation material [€/m^3]
$C_{tc\text{-}wall}$	energy cost of space cooling to cover heat transmission of opaque external wall [€]
$C_{th\text{-}wall}$	energy cost of space heating to cover heat transmission of opaque external wall [€]
CDD_{26}	cooling degree-days [K•d/a]
D_5	the number of days with daily temperature lower than 5 ℃ [d/a]
D_{25}	the number of days with daily temperature higher than 25 ℃ [d/a]
f_{sol}	solar fraction [%]
g	"g-value", solar heat gain factor [-]
HDD_{18}	heating degree-days [K•d/a]
i	interest rate [%/a]
N	service life of thermal insulation [a]
n	time period [a]
PE	primary energy factor [-]
Qh	heating demand [kWh / (m^2a)]
Q_{AUX}	auxiliary energy [kWh / (m^2a)]
$Q_{c\text{-}window}$	increased cooling demand by using 1m^2 window instead of wall in cooling period [kWh/a]
$Q_{h\text{-}window}$	decreased heating demand by using 1m^2 window instead of wall in heating period [kWh/a]
$Q_{tc\text{-}wall}$	heat-gain of opaque wall in cooling period [kWh/a]
$Q_{th\text{-}wall}$	heat-loss of opaque wall in heating period [kWh/a]
$Q_{tc\text{-}window}$	heat-gain of window in cooling period [kWh/a]
$Q_{th\text{-}window}$	heat-loss of window in heating period [kWh/a]
$Q_{sg\text{-}h}$	solar gain in heating period [kWh/a]
Q_{sol}	solar radiation on surface [kWh / (m^2a)]
Q_E	yearly final energy demand [kWh / (m^2a)]
Q_P	yearly primary energy demand [kWh / (m^2a)]
Q_U	yearly useful energy demand [kWh / (m^2a)]
R_{wo}	total thermal resistance of external wall except thermal insulation [(m^2K)/W]
SPF	seasonal performance factor [-]
$T_{c\text{-}month}$	average outdoor temperature in the coldest month [℃]
$T_{h\text{-}month}$	average outdoor temperature in the hottest month [℃]
t_c	cooling duration [h]
t_h	heating duration [h]
ΔT_c	temperature difference between indoor and outdoor air in cooling period [K]
ΔT_h	temperature difference between indoor and outdoor air in heating period [K]

U_{wall} heat transfer coefficient of external wall [W/ (m^{2}K)]

U_{window} heat transfer coefficient of glazing [W/ (m^{2}K)]

ΔU difference of U-value between glazing and opaque wall [W/ (m^{2}a)]

λ_M heat conductivity of insulation material [W/ (m•K)]

δ_M thickness of thermal insulation [m]

ŋ solar heat gain effectiveness [-]

$ŋ_h$ efficiency of heating system [-]

$ŋ_c$ efficiency of cooling system [-]

Chapter 1

INTRODUCTION

1.1. Problem Definition

Since energy crisis in 1970s, there are growing worldwide concerns about energy saving. Industry, building and transportation are top three energy consumers. In the year 2010, residential sector accounted for about 10% of total energy consumption in China (Fig 1.1.1). With the increasing requirement of living standard, energy consumption in residential building keeps growing. Energy efficient residential building is required all over the world. As one of the biggest countries in the world, China has its responsibility to reduce energy consumption, especially in residential buildings.

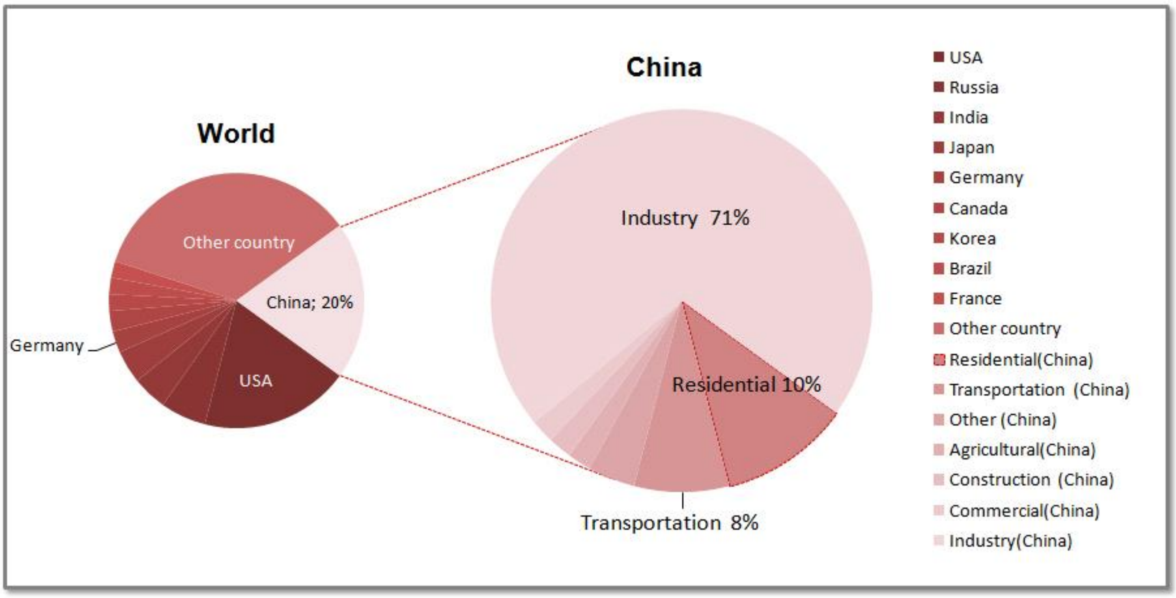


Fig 1.1.1 Total energy consumption of various countries（2010） [1] [2]

Chinese energy efficiency efforts started from 1980s. In order to reduce energy consumption, standards and regulations are published. Demonstration buildings such as Ultra-low energy building in Tsinghua University (in Beijing) were built for research (Fig 1.1.2). In 2009, the first Energy Performance Certificate (Energieausweis) for Chinese residential building was awarded to the project “Nanjing Chengkai Yuyuan” (Fig 1.1.3). Residential building “C12” in project “Water Front” is built as the first “passive house” in China.

Though energy efficiency in demonstration buildings is very good, it is still hard to persuade clients to use advanced building service system or better thermal insulation. Too high cost is the most important reason. In demonstration buildings, energy efficient strategies are collected together for research purpose. For clients, it is important to know which strategy is the most suitable for the building considering the cost and special climate condition. In this thesis, energy efficient strategies are discussed and compared under different climate conditions. Primary energy demand and total cost in service life are two indexes. Based on these, suggestions about energy efficient multi-story residential buildings will be convincing.

Fig 1.1.2 Ultra-low energy demonstration building in Tsinghua University, Beijing (China)

(Picture source: http://www.archcy.com)

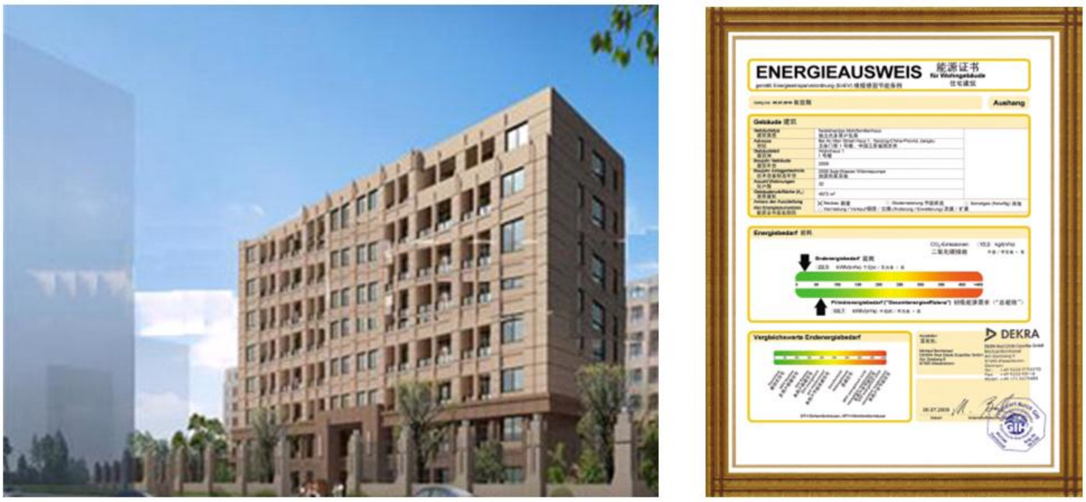


Fig 1.1.3 Chengkai Yuyuan, Nanjing (China)

(Picture source: (left) http://www.cnkg.com.cn; (right): http://epaper.yangtse.com)

1.2. Terms and Definitions

1.2.1. Useful energy and Final energy

There are three forms of energy in the discussion of building energy demand, which are useful energy (Q_U), final energy (Q_E) and primary energy (Q_P). As description in the book EneryPLUS, “useful energy is available energy used for space heating, ventilation, lighting, etc. and meets the user’s needs for hot water, cooking, refrigerating, washing, etc. Final energy used refers to the energy fed to the building continuously or intermittently and is generally recorded by meters (electricity, heating and gas) or in terms of volume (wood and coal)”. [3] Final energy demand could be calculated by useful energy demand and system efficiency (such as heating system efficiency “η_h”) or seasonal performance factor of building service system (SPF) (Fig 1.2.1).

Useful energy demands (such as heating demand and cooling demand) could not be added together, because of different system efficiency. Final energy demand should not be summed or compared either, because their fuels have different primary energy factor (PE). Energy demand or consumption could be summed and compared only in the form of primary energy.

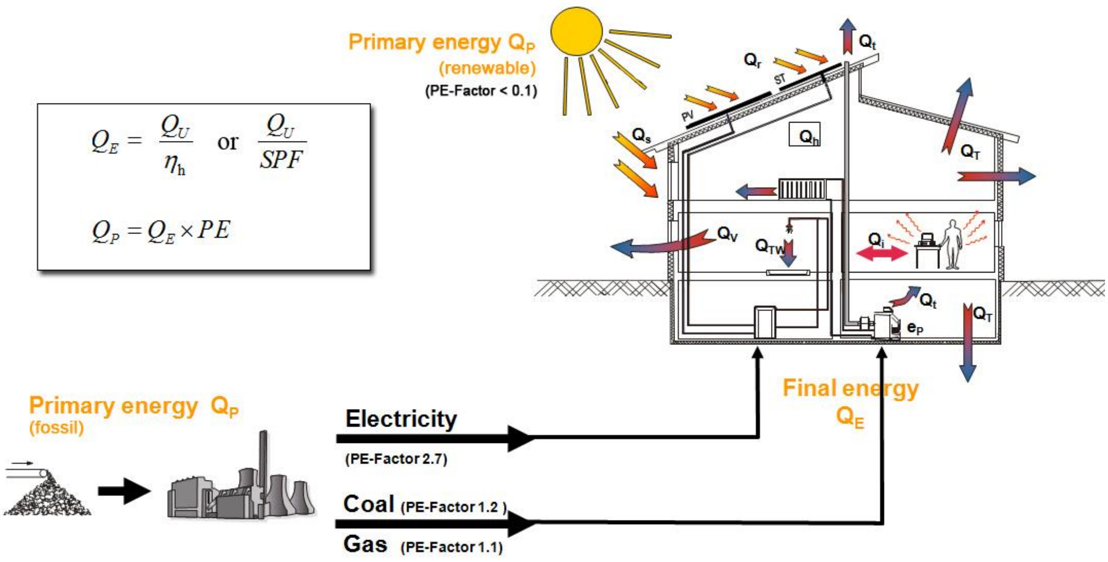


Fig 1.2.1 Final energy and primary energy

(Picture source: Institut für Gebäude- und Solartechnik, TU Braunschweig)

1.2.2. Primary energy

"The primary energy is calculated as the sum of the primary energy expenditure costs of the final energy used for heating, cooling and electricity. The expenditure costs include the cost of handling from the depository of the fuel resource to the user's building (final energy)." [3]

Primary energy demand could be calculated by final energy demand and PE-factors of fuels (Fig 1.2.1). PE-factor reflects the quality of the energy generation and distribution. In this thesis, PE-factors of coal, gas and electricity are 1.2, 1.1 and 2.7, respectively.

1.2.3. Energy efficient

With the development of research on building energy saving, many energy concepts have emerged, such as "Low-energy", "zero energy", "passive" and "Energy PLUS" (Chapter 3.1.1). In this thesis, "energy efficient" means lower primary energy demand. Residential building, which has lower primary energy demand than the basic model and reference system, is named as "energy efficient residential building".

1.3. Research Methodology

The purpose of this research is finding comprehensive concepts of energy efficient multi-story residential building in China. Five cities (Urumqi, Beijing, Shanghai, Guangzhou, Kunming) are chosen as representative cities in various climate zones (severe cold, cold, hot summer and cold winter, hot summer and warm winter, warm). The main part of this research has two branches, which are building envelope and building service technology.

A model of common multi-story residential building, which has 18 floors, is built in the software "DesignBuilder" as basic model. Three types of existing building service systems are chosen as reference systems.

In the first parameter study, thermal insulation of external wall, glazing types, window-to-wall ratio are discussed under selected 5 climate conditions. According to manual calculation and simulation, optimal thickness of thermal insulation (external wall), optimal window-to-wall ratio and glazing types are shown under each climate condition.

In the second parameter study, "solar thermal system" (system-A) and "ground-coupled heat pump system" (system-B) are discussed as two advanced building service systems with high potential use of renewable energy. Primary energy demand and total cost in service life are compared with reference systems. Software "Trnsys" and "PV*SOL" are used as the simulation programs.

After that, system-B is developed by using air-source heat pump instead of eclectic water heater to supply domestic hot water. This improved system is named as "system-C". In system-D, PV modules are designed on the roof. PV system connects to electricity grid.

Then, system-A, system-B, system-C and system-D are compared together. In the view of primary energy saving, system-D (combination of ground-coupled heat pump and PV system) is the best choice in each city. Considering government fund for PV systems, combination of ground-coupled heat pump and PV system is also an economic strategy for multi-story residential buildings in China.

This research could be shown as Fig 1.3.1.

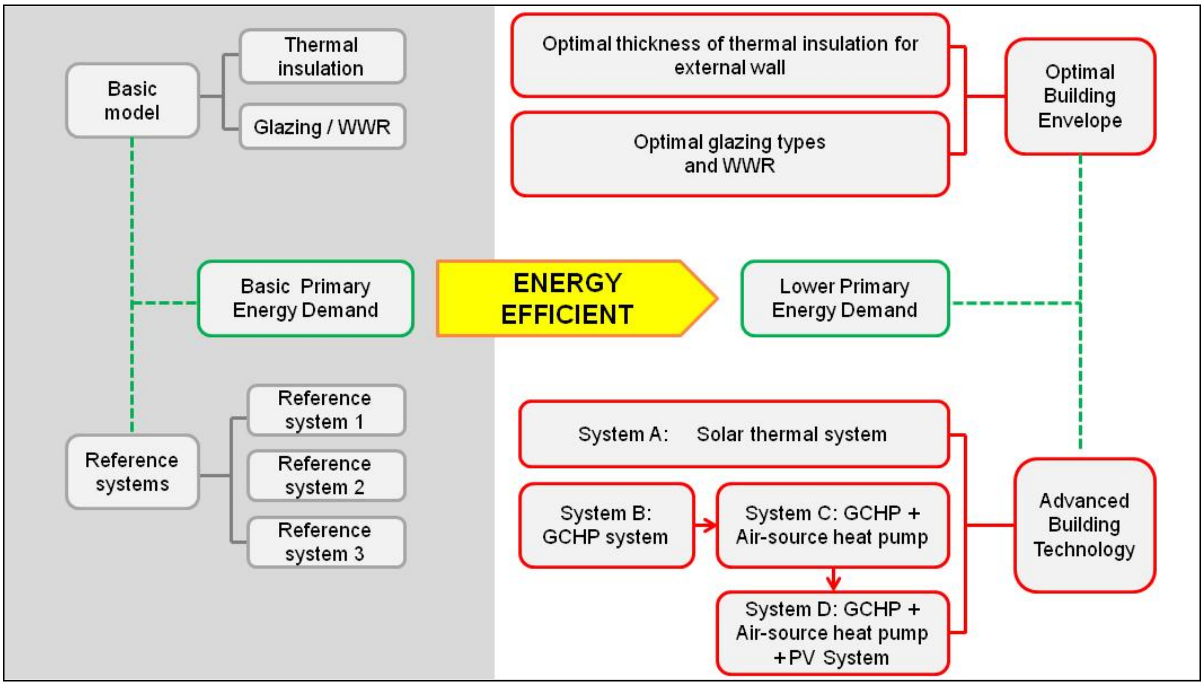


Fig 1.3.1 Research methodology

1.4. Simulation Programs

Three simulation programs are chosen to study different aspects in each part of this research (Fig 1.4.1).

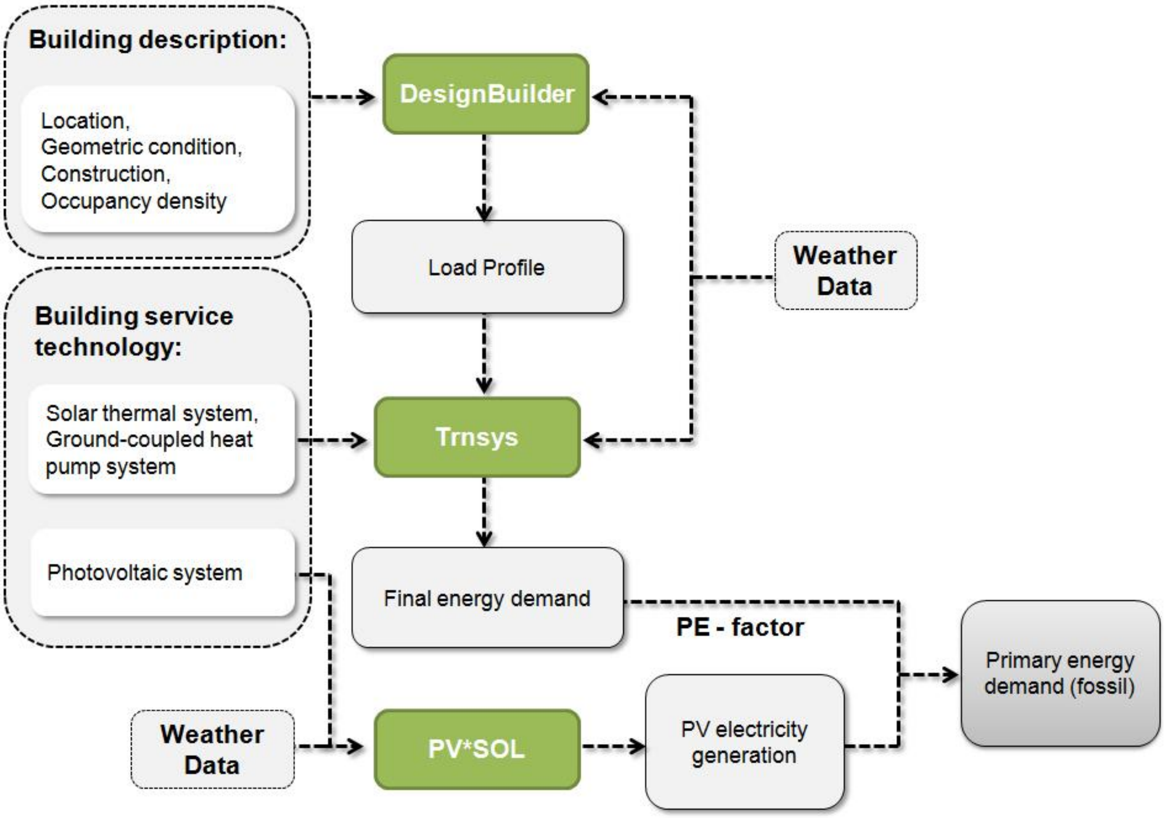


Fig 1.4.1 Simulation programs used in the research

1.4.1. DesignBuilder

DesignBuilder is such a simulation program, which uses EnergyPlus[1] simulation engine to calculate the energy performance of the building. It is suitable for Architects to do building design, because of its friendly interface and intuitive modeling function (Fig 1.4.2). In this thesis, building model is simulated in this program with basic information about building design. Load profiles of space heating and cooling are exported in table format for further study.

[1] EnergyPlus is the U.S. DOE building energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows.

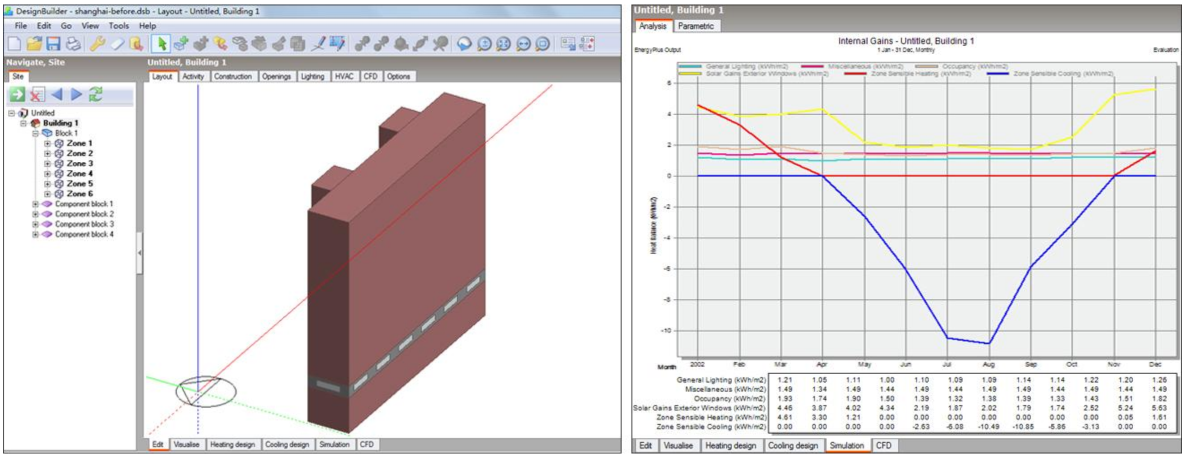


Fig 1.4.2 Model and simulation in DesignBuilder

1.4.2. TRNSYS

Compared with DesignBuilder, TRNSYS is more intuitive in system design. In this program, building service system is described by lots of connected components (found in TRNSYS library), which are specified by user. Parameters and connecting manners of components could be adjusted. Simulation results will be exported in different formats according to output-components. In this thesis, TRNSYS is used for the simulation of solar thermal system and ground-coupled heat pump system. Final energy demand of different systems is expected simulation result.

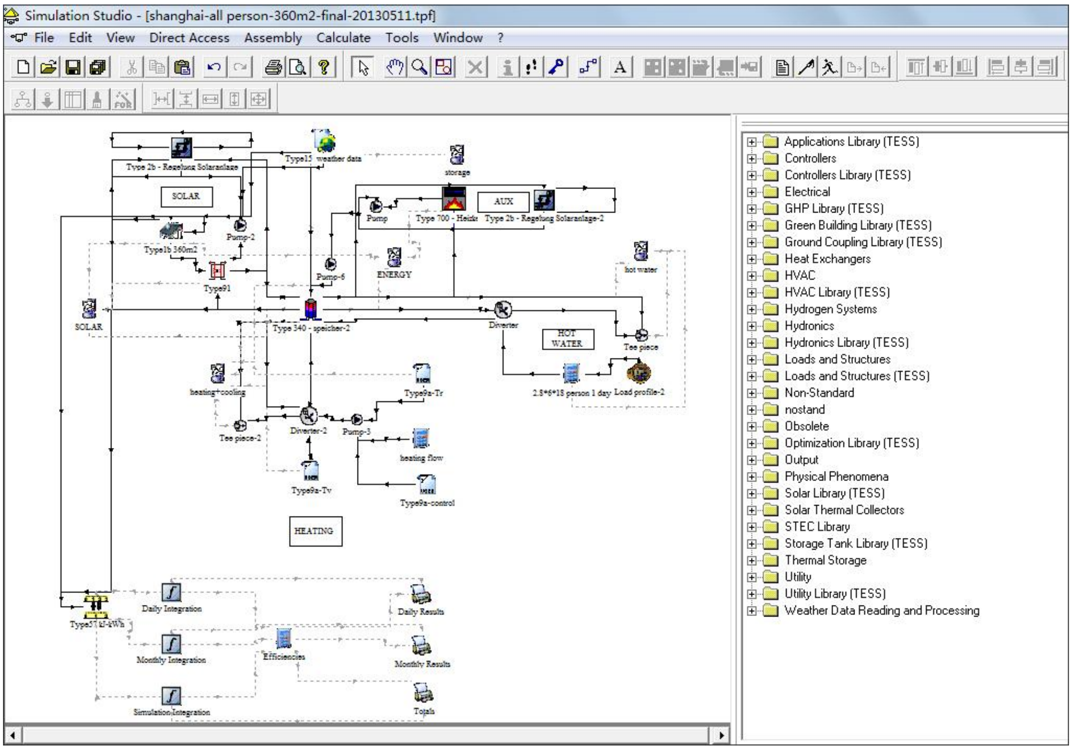


Fig 1.4.3 Model of solar thermal system in TRNSYS

1.4.3. PV*SOL Expert

Though it is possible to simulate Photovoltaic system in TRNSYS, using software “PV*SOL® Expert” is more comfortable for architects. Technical Data of PV module and inverters from different companies could be found in its library. The cabling of PV system is visible and could be easily adjusted. In this thesis, Photovoltaic system is simulated by this program to calculate the yearly PV electricity production.

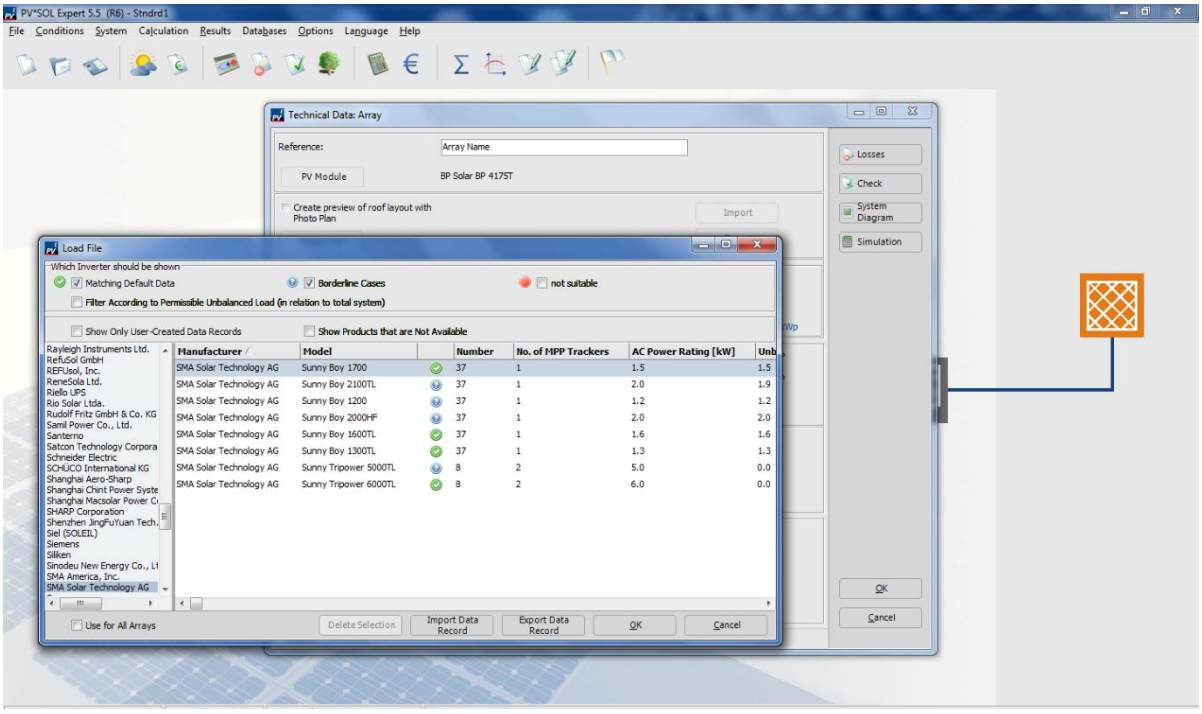


Fig 1.4.4 Modeling Photovoltaic system in PV*SOL

Chapter 2

BACKGROUND

2.1. Climate conditions

2.1.1. Chinese Climate Zones

According to the Standard GB50176-93 [4], there are 5 different climatic zones in China, which are severe cold zone, cold zone, hot summer and cold winter zone, hot summer and warm winter zone, and warm zone. They are identified according to 4 main values, which are average temperature in the coldest month ($T_{c\text{-}month}$), average temperature in the hottest month ($T_{h\text{-}month}$), the number of days with daily temperature lower than 5℃ (D_5) and the number of days with daily temperature higher than 25℃ (D_{25}). They are shown as the Table 2.1.1.

Zone	$T_{c\text{-}month}$	$T_{h\text{-}month}$	D_5	D_{25}
severe cold	≤-10 ℃		≥145 d/a	
cold	-10 ~ 0 ℃		90 ~ 145 d/a	
hot summer and cold winter	-10 ~ 0 ℃	25 ~30 ℃	0 ~ 90 d/a	40 ~ 110 d/a
hot summer and warm winter	>10 ℃	25 ~ 29 ℃		100 ~ 200 d/a
warm	-13 ~ 0 ℃	18 ~ 25 ℃	0 ~90 d/a	

Table 2.1.1 Climate zones in China

Fig 2.1.1 Map of Chinese climate zones

Severe cold zone

"Severe cold zone" is the coldest climate zone among five climate zones. More than half part of northern China belongs to this zone. The average temperature in the coldest month could be lower than -10℃. There are more than 145 days each year with the daily temperature lower than 5℃. Heating system is strongly required, while heat-resistant in summer could be ignored. Urumqi could be the representative city in severe cold zone.

Cold zone

Climate condition in "cold zone" is warmer than that in severe cold zone. The average temperature in the coldest month is between -10℃ and 0℃. There are 90~145 days with average temperature lower than 5℃ each year. Combined with severe cold zone, the whole area of northern China is nearly covered. Space heating is still the most important demand. However, in some district, heat-resistant in summer should also be involved into discussion. Beijing, which is the capital of China, could be the representative city of this climate zone.

Hot summer and cold winter zone

"Hot summer and cold winter zone" has the most complicated climate condition. The monthly temperature fluctuates during the year. The average temperature could be lower than 0℃ in winter, while in summer it could reach 30℃. Besides heating demand, the energy demand for cooling should also be considered. The southeast of China is mainly covered by this climate zone. Shanghai could be chosen as the representative city.

Hot summer and warm winter zone

Compared with "Hot summer and cold winter zone", the winter climate condition in "Hot summer and warm winter zone" is better. The average temperature in the coldest month is higher than 10℃. However, the number of days, which has average temperature higher than 25℃, is nearly as double as "Hot summer and cold winter zone". In this climate zone, cooling system is strongly required, while heating demand could be ignored. Coastal cities in southern China belong to this zone. Guangzhou could be taken as a representative city of them.

Warm zone

The most comfort climate zone in China is "warm zone". The province Yunnan almost occupies the whole zone. Air temperature is neither too low nor too high. Kunming, which is the provincial capital of Yunnan, is a representative city in warm zone. The climate here is like spring all year round. Because of that, Kunming has a nick name "spring city".

As shown above, these five climate zones are totally different and have special requirements for building service system. In this research, Urumqi, Beijing, Shanghai, Guangzhou and Kunming are chosen to represent severe cold zone, cold zone, hot summer and cold winter zone, hot summer and warm winter zone and warm zone, respectively. Characteristic requirements for building service system in each climate zone will be discussed by analyzing its representative city in Chapter 2.1.2 (Fig 2.1.2).

Fig 2.1.2 Representative cities

2.1.2. Climate Characteristics in representative cities

The program “Climate consultant 5.0” is used to indicate climate characteristics of each city. Weather data could be read and shown intuitively in this program (Fig 2.1.3). All weather data come from ASHRAE International Weather for Energy Calculations (IWEC) data.

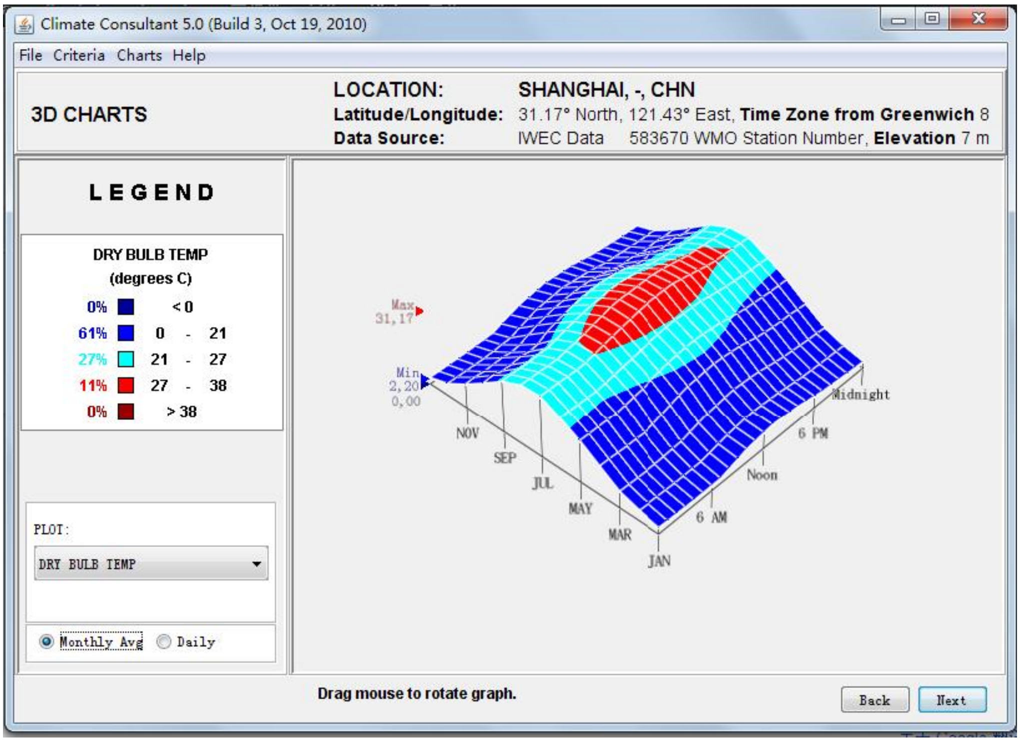


Fig 2.1.3 The 3D-chart of dry bulb temperature in Shanghai

ASHRAE Standard 55-2004 PMV (Predicted Mean Vote) model is chosen to define comfort zones. The PMV is the average comfort vote, which uses a seven-point thermal sensation scale (-3 ~ +3). Zero is the ideal value, which means thermal neutrality. Air temperature, mean radiant temperature, metabolic rate (met), clothing insulation (clo), air speed, and humidity are considered in the calculation of PMV model. If PMV value generated by the model is within the recommended range (-0.5<PMV<+0.5), the conditions are within the comfort zone (Fig 2.1.4).

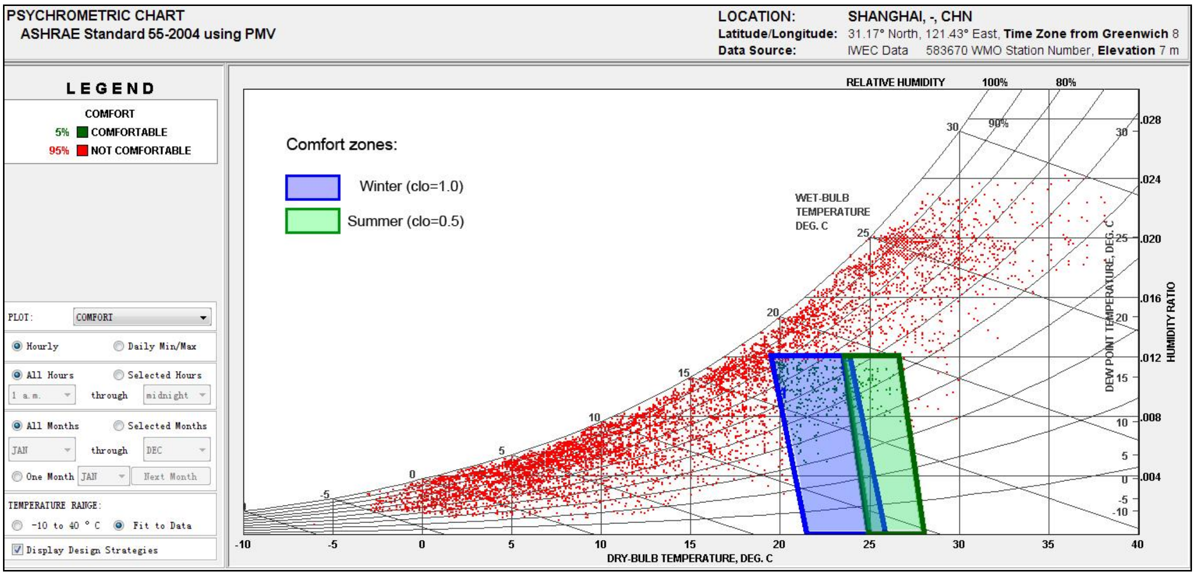


Fig 2.1.4 Example of thermal comfort zone (Shanghai)

2.1.2.1. URUMQI

Urumqi (43.83° N, 87.53° E) locates in “severe cold climate zone”. Annual average outdoor temperature is about 7℃. In coldest month, average air temperature could be under -15℃. According to ASHRAE Standard 55-2004 PMV model, 17% of hours during the year are in comfort zone. Most hours are discomfort because of the low air temperature. There is big energy demand for space heating in this city.

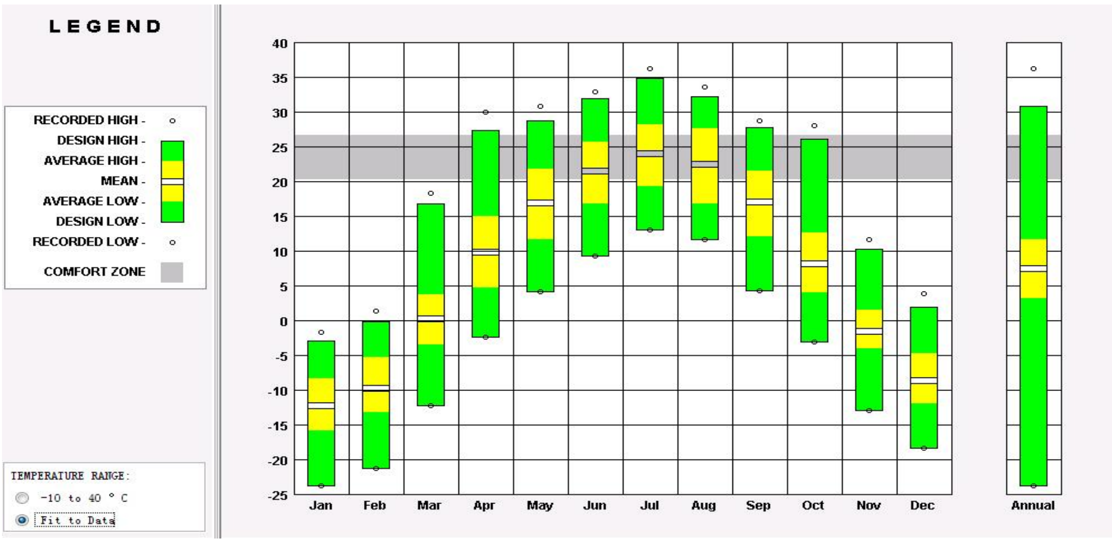


Fig 2.1.5 Temperature chart in Urumqi

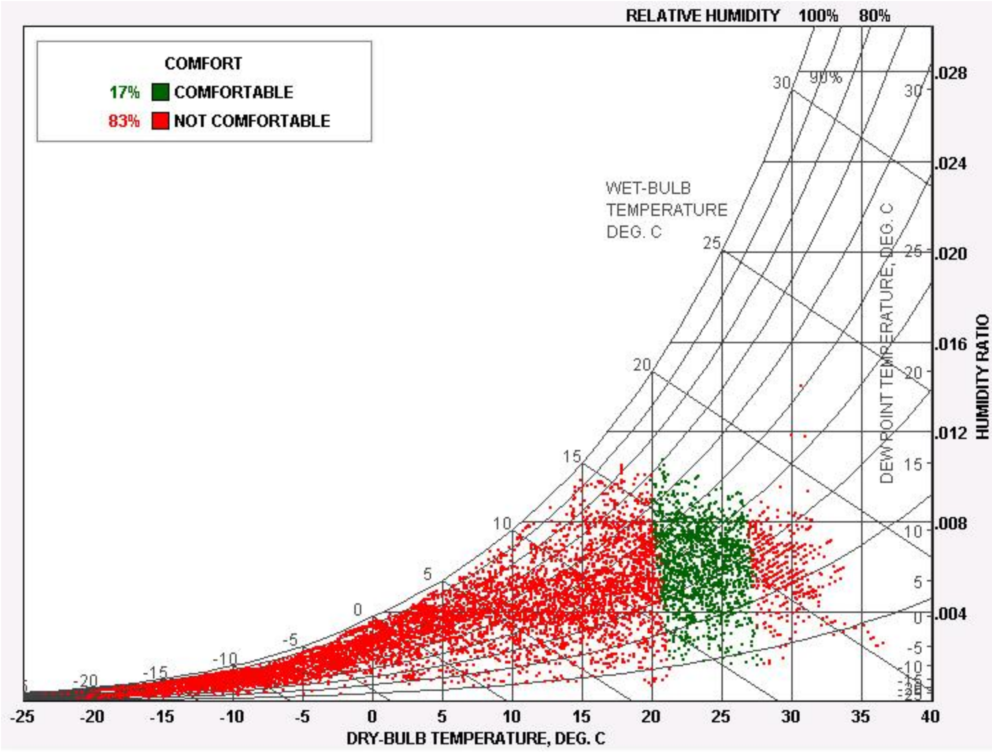


Fig 2.1.6 Psychrometric chart in Urumqi

2.1.2.2. BEIJING

Beijing (39.8° N, 116.47° E) locates in "cold climate zone". Annual average outdoor temperature is about 12.5℃. In coldest month, average air temperature could be under -8℃. According to ASHRAE Standard 55-2004 PMV model, only 10% of hours during the year are in comfort zone. Most hours are discomfort because of the low air temperature. Compared with Urumqi, the climate in Beijing is warmer. However, heating demand is still huge in this city.

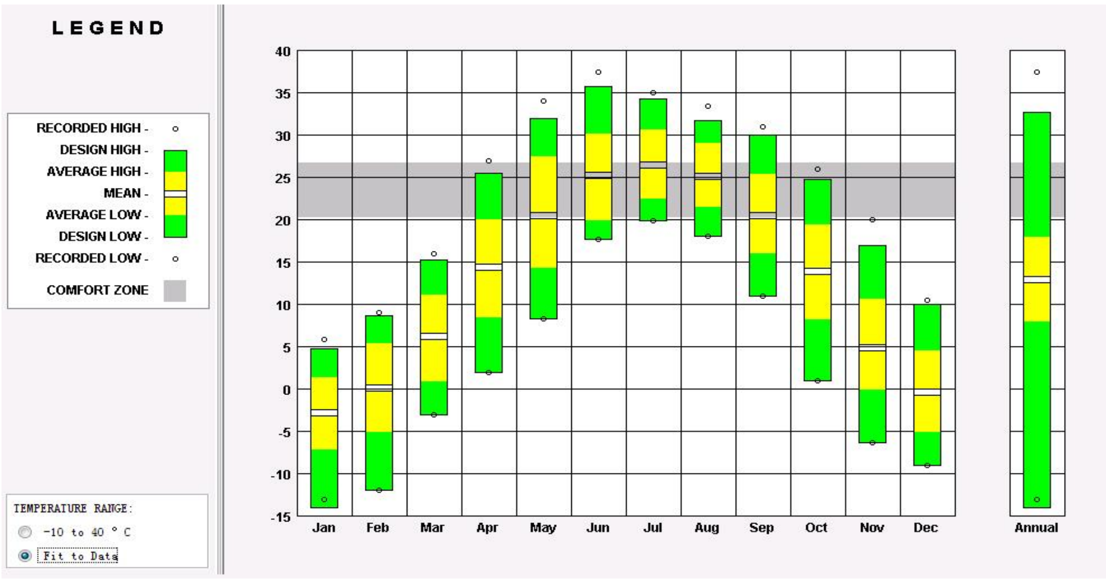


Fig 2.1.7 Temperature chart in Beijing

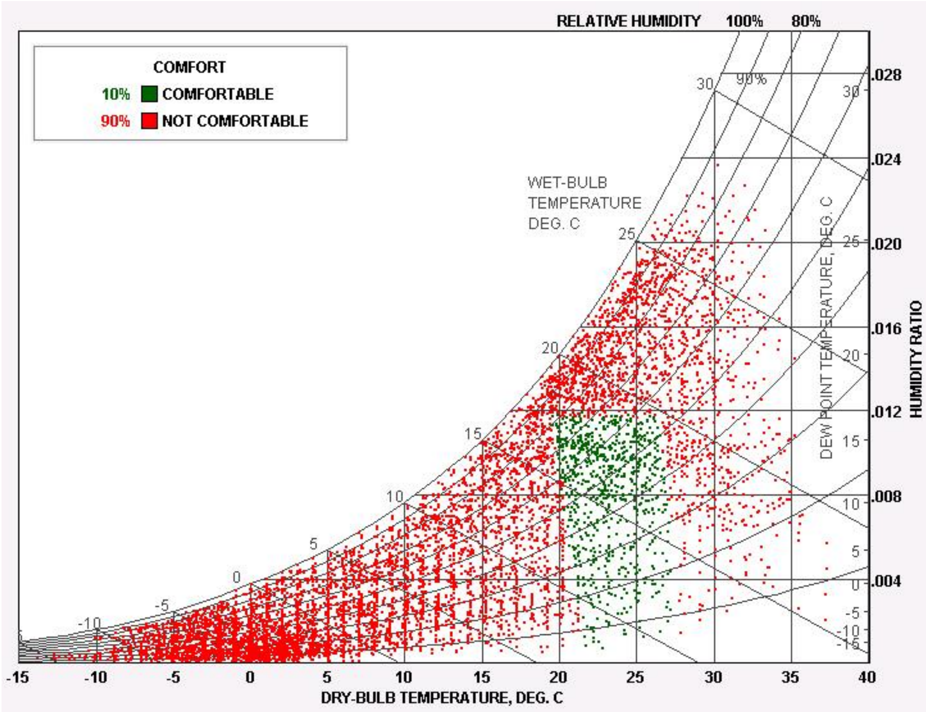


Fig 2.1.8 Psychrometric chart in Beijing

2.1.2.3. SHANGHAI

Shanghai (31.17° N, 121.43° E) locates in "hot summer and cold Winter zone". Annual average outdoor temperature is about 16℃. In coldest month, average air temperature could be under 2℃. In hottest month, average air temperature could be up to 32℃. According to ASHRAE Standard 55-2004 PMV model, only 5% of hours during the year are in comfort zone. There are both big energy demands for space heating and cooling. Relative humidity is also high. Energy demand for dehumidification needs to be considered.

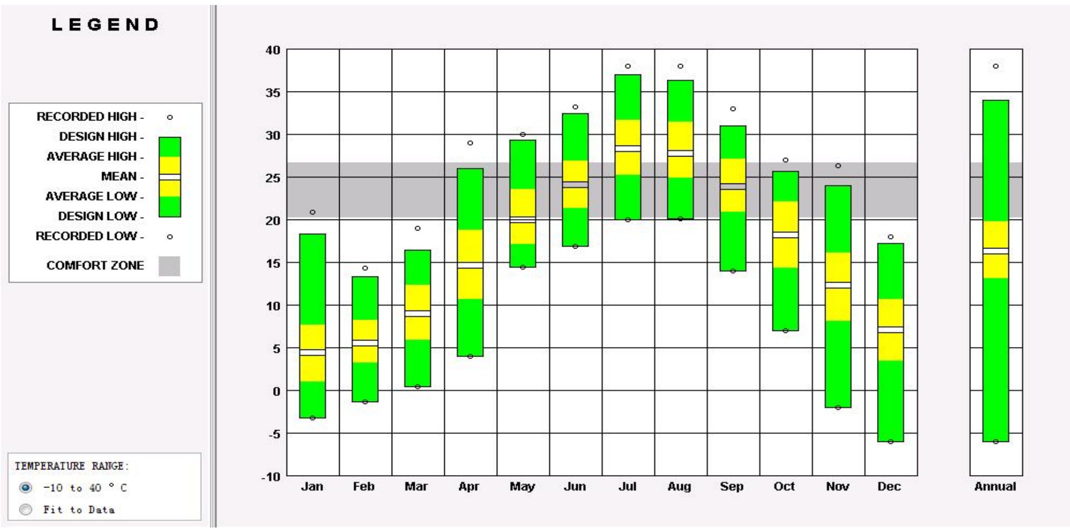


Fig 2.1.9 Temperature chart in Shanghai

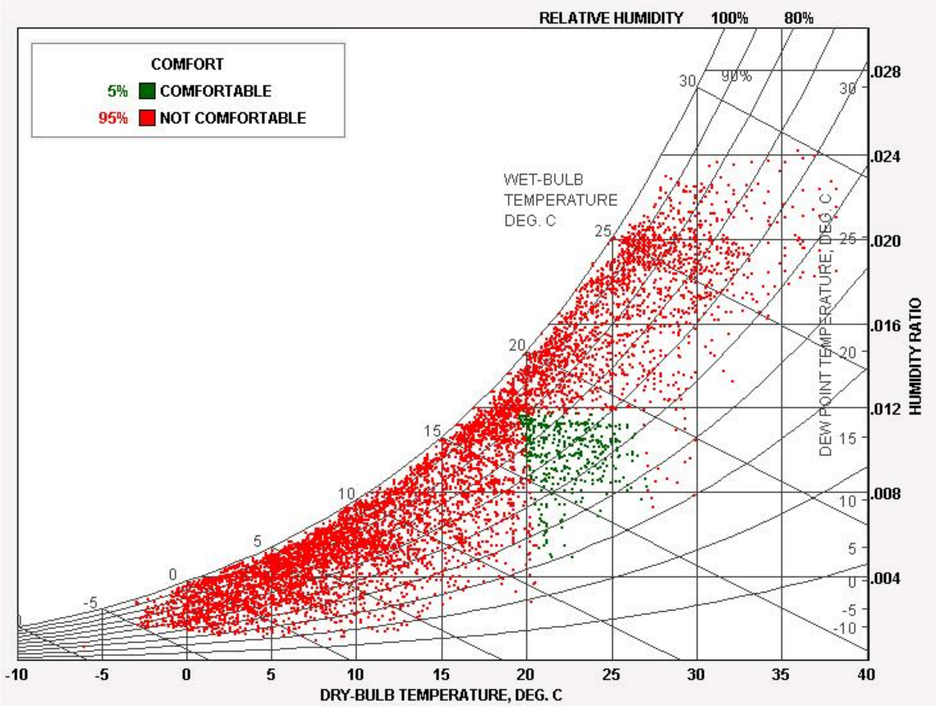


Fig 2.1.10 Psychrometric chart in Shanghai

2.1.2.4. GUANGZHOU

Guangzhou (23.13° N, 113.32° E) locates in "hot summer and warm Winter zone". Annual average outdoor temperature is about 23℃. In coldest month, average air temperature is above 12℃. In hottest month, average air temperature could be up to 33℃. According to ASHRAE Standard 55-2004 PMV model, 8% of hours during the year are in comfort zone. Most hours during the year are discomfort because of the high air temperature and relative humidity. Cooling demand is dominant in this city.

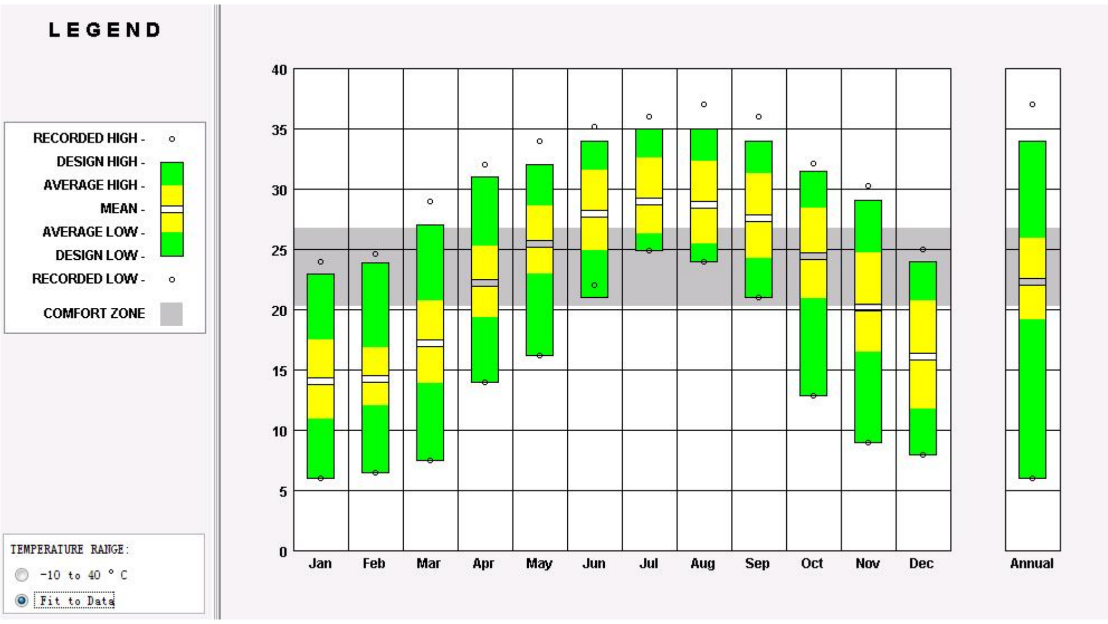


Fig 2.1.11 Temperature chart in Guangzhou

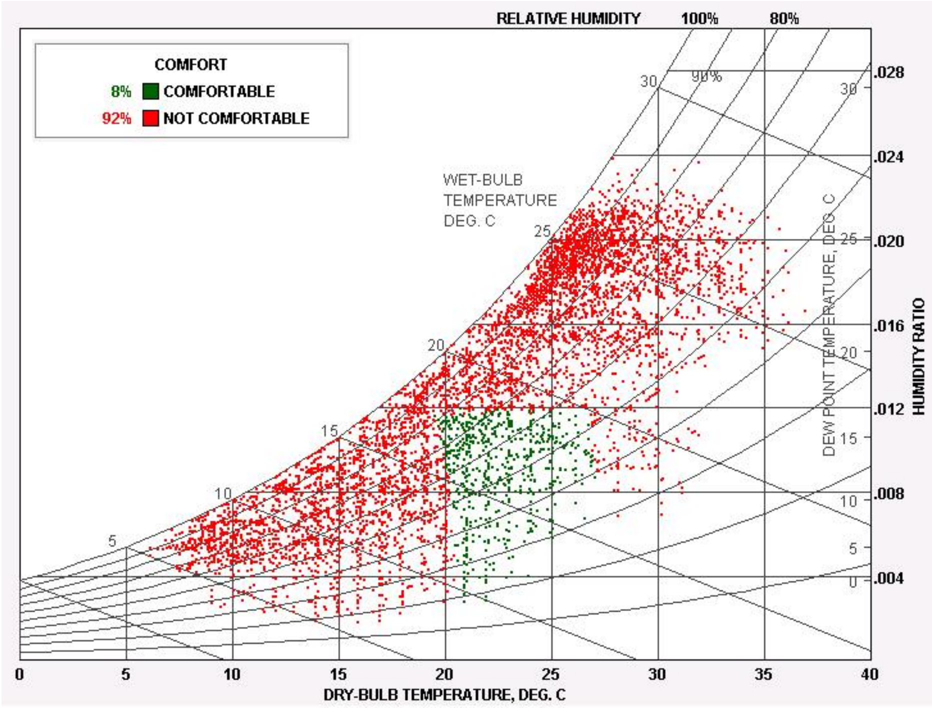


Fig 2.1.12 Psychrometric chart in Guangzhou

2.1.2.5. KUNMING

Kunming (25.02° N, 102.68° E) locates in “warm climate zone”. Air temperature keeps moderate during the year. Annual average outdoor temperature is about 16℃. According to ASHRAE Standard 55-2004 PMV model, 17% of hours during the year are in comfort zone. Compared with other four cities, both heating and cooling demands are less.

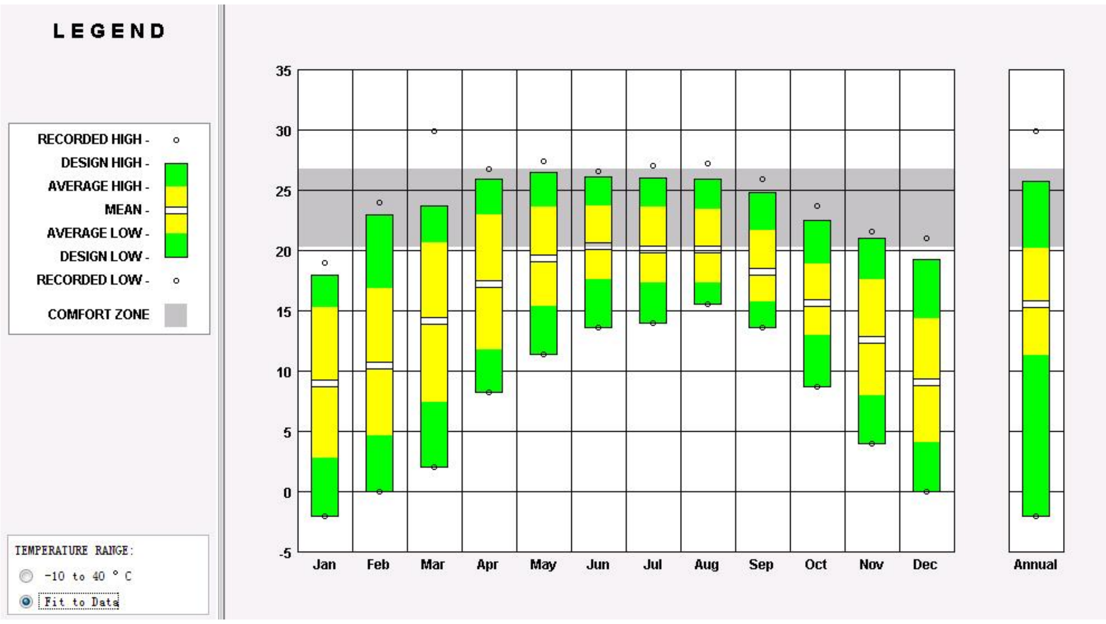


Fig 2.1.13 Temperature chart in Kunming

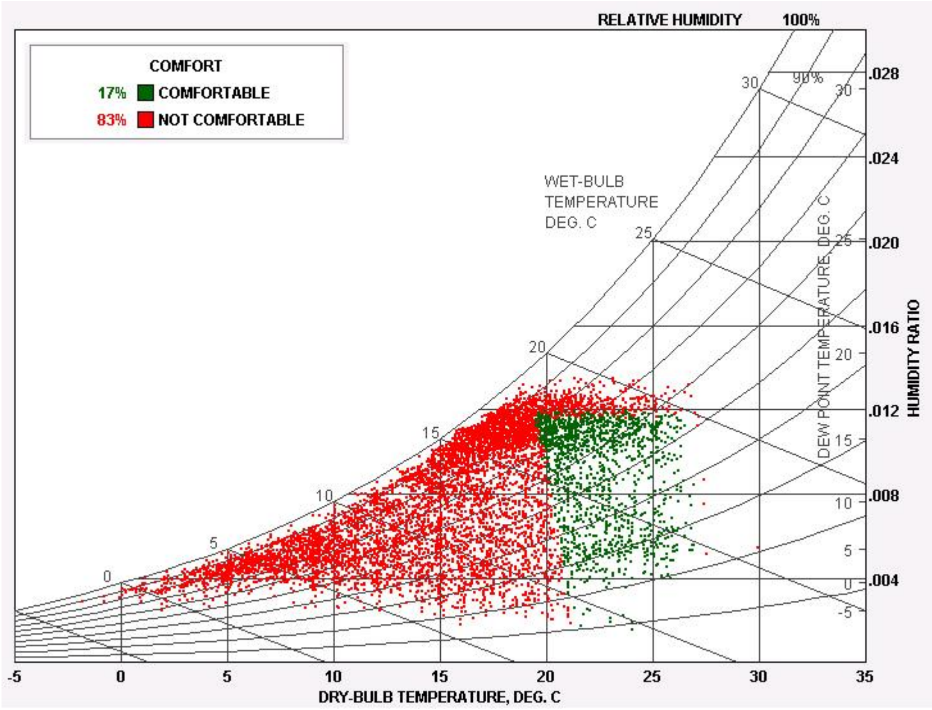


Fig 2.1.14 Psychrometric chart in Kunming

2.2. Basic model and reference building service systems

2.2.1. Basic model

In order to show energy saving effect of different strategies, a basic model of Chinese multi-story residential buildings is taken as reference.

2.2.1.1. Building design and basic information

This basic model is built in software "DesignBuilder" based on a real residential building, which has common design in China. It is a multi-story residential building with 18 floors. There are 6 apartments on each floor. Floor area is between 80 m^2 to 100 m^2.Two lifts work as vertical connection. Based on this real building, a basic model is developed (Fig 2.2.1).

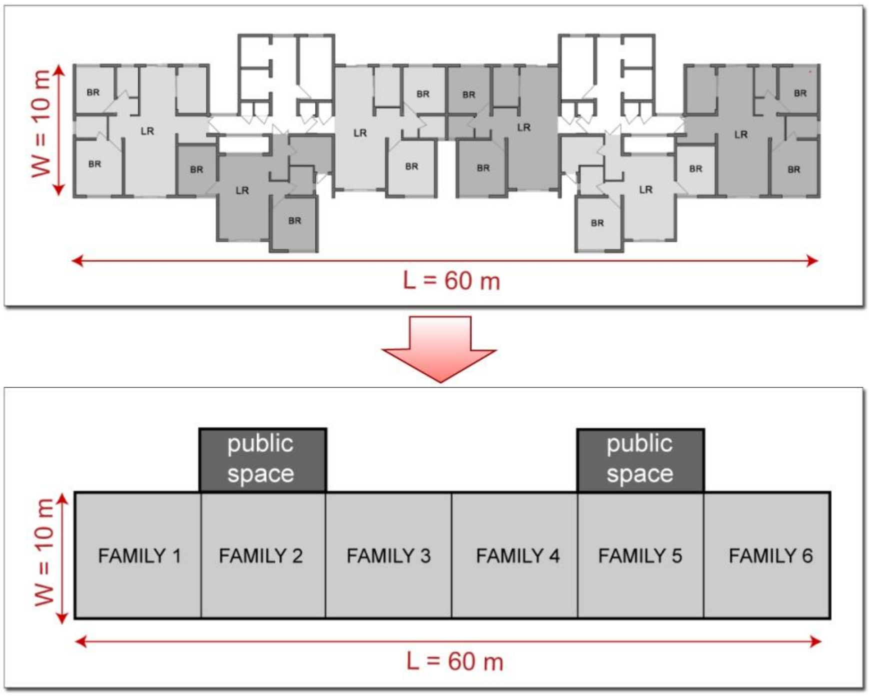


Fig 2.2.1 Floor plan of basic building model

The model is made in the software DesignBuilder as Fig 2.2.2. It is an 18-floors residential building. On each floor, there are 6 apartments with 100 m^2 floor area for each. The density of occupancy is 0.03 person/m^2.

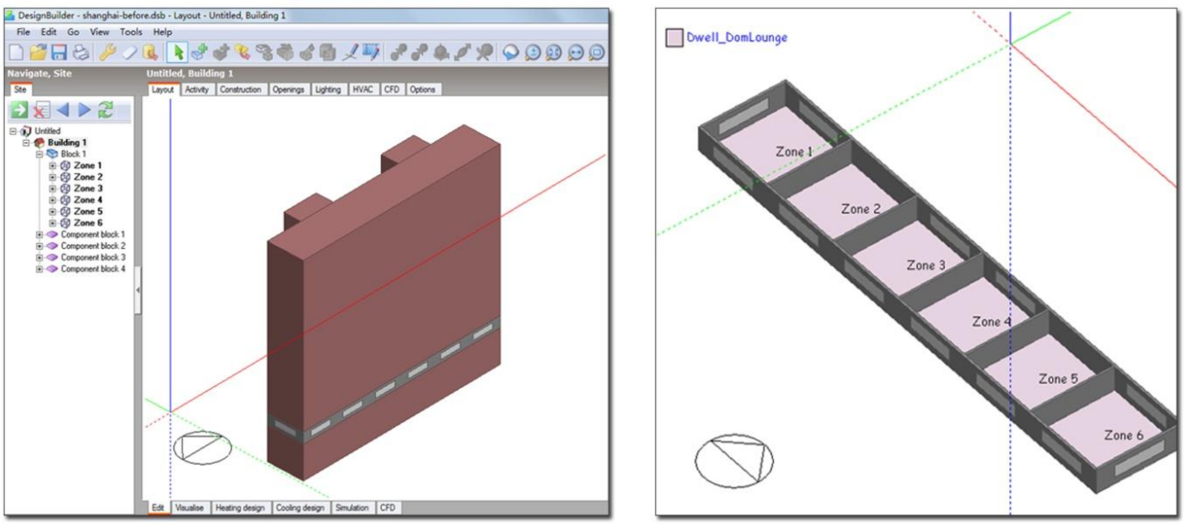


Fig 2.2.2 Basic building model in software “DesignBuilder”

2.2.1.2. Envelope of basic model

The construction of external wall is similar among 5 climate zones except the thickness of its insulation layers. Fig 2.2.3 shows details of wall construction in basic building model. Glazing type in basic model is 6mm+13mm air+6mm double clear glazing (g=0.7, U=2.7 W/ (m^2K)). Window-to-wall ratio (WWR) is 30% on each external wall.

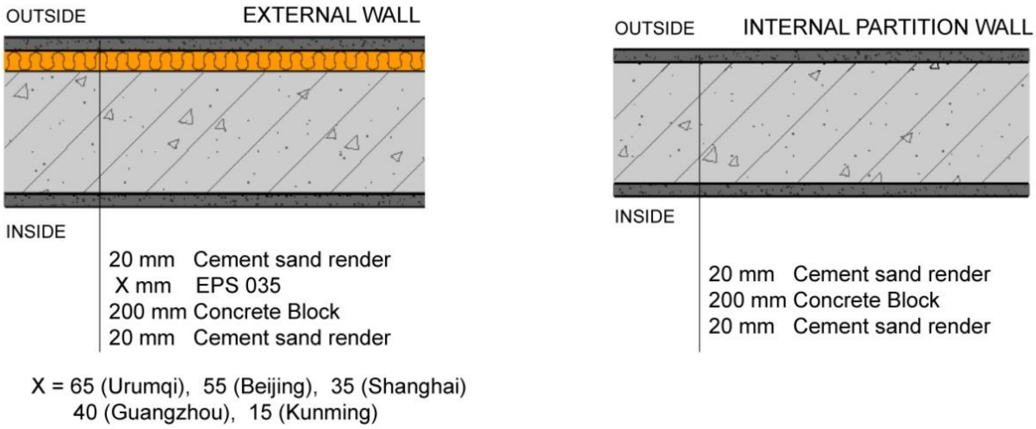


Fig 2.2.3 Wall construction of basic building model

In the basic model, insulation material for external wall is expanded polystyrene (EPS). The thickness of EPS is calculated according to the required heat transfer coefficient of external wall (U-value). [4] [5] [6] [7]

	U_{wall}	δ_M of EPS λ_M = 0.035W/(m•K)
	W/ (m^2K)	mm
Urumqi	0.45	67
Beijing	0.55	53
Shanghai	0.80	33
Guangzhou	0.70	40
Kunming	1.50	13

Table 2.2.1 Thickness of external wall insulation layers

2.2.2. Building service system

Building service system, which is discussed in this research, supplies domestic hot water, space heating and space cooling. Lighting and appliances are also considered. Existing building service systems among different climate zones are shown as follow.

2.2.2.1. Space heating system

"District-heating area" is defined in "Code for design of heating ventilation and air conditioning (GB50736-2012)" [8]. There are no less than 90 days in a normal year with daily average temperature lower than 5℃ (included). Generally speaking, northern part of China is district-heating area, while southern part is no-district-heating area. Compared with climate zones, "severe cold zone" and "cold zone" belong to district-heating area, other three zones belong to no-district-heating area.

In district-heating system, heat is generated by coal-boilers or gas-boilers in the central heating plant and distributed into each building through distribution network. Radiators, which locate in each apartment, are heat-exchangers. Heating systems in Urumqi and Beijing both belong to this type. The fuel of district-heating system in Urumqi is coal, while in Beijing is gas. The efficiency of gas-boiler heating system (η = 0.9) is a little higher than coal-boiler heating system (η = 0.7).

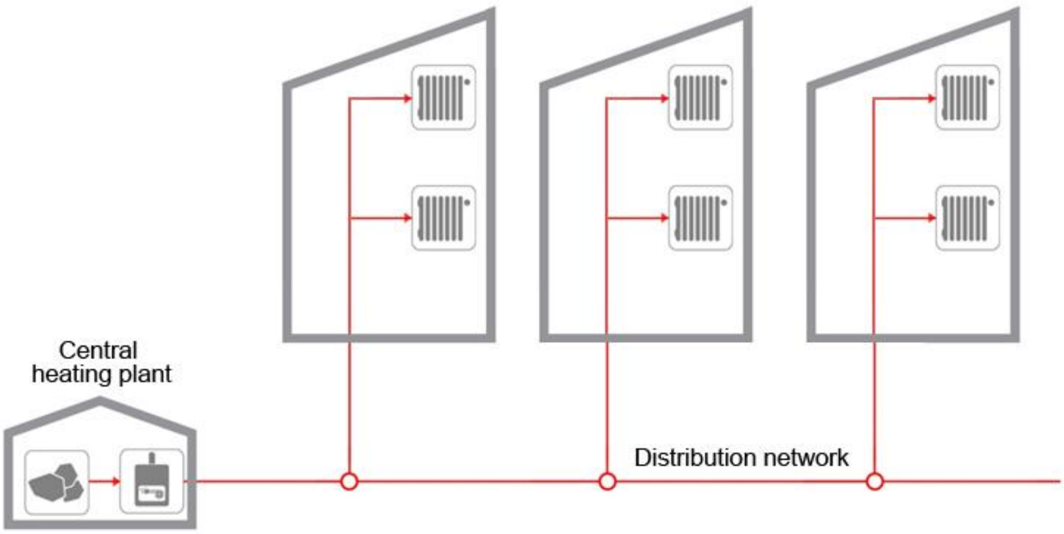


Fig 2.2.4 District-heating system

Compared with individual heating system, the investment for district-heating system is more expensive and the system construction is more complicated. Heat loss during the process of distribution is large. It is also difficult to adjust individually, so that there is a big amount of energy waste because of "over heating". However, when district-heating is supplied by CHP (combined heat and power generation) instead of coal-boilers or gas-boilers, there will be the possibility of free heating. In recent years, the proportion of CHP is growing [9].

Shanghai, Guangzhou and Kunming locate in no-district-heating area. Electric heater and split air handling unit (Fig 2.2.5) are popular heating equipments in this area. Electric space-heater converts electricity into heat directly, while air-conditioner works as an air-to-air heat pump. So the heating efficiency of split air handling unit is much higher than electric heater.

2.2.2.2. Cooling system

The most popular cooling equipment in Chinese residential buildings is split air handling unit ("Air conditioner"). It works as an air-to-air heat pump. In no-district-heating area, reversible split air handling unit is also used for heating. In this thesis, the seasonal performance factor (SPF) of split air handling unit is considered to be 1.9 for heating and 2.3 for cooling. [5]

Fig 2.2.5 Split air handling unit

2.2.2.3. Domestic hot water

In Chinese residential buildings, domestic hot water is supplied in various ways. Generally it is heated by small size water-heater in each flat. Gas or electricity is energy source. Sometimes it is centrally generated in central heating plant, but it is uncommon.

2.2.2.4. Lighting and appliances

In this thesis, lighting and appliances are not discussed in detail. 5.3 kWh/ (m^2a) and 5.1 kWh/ (m^2a) are used as yearly electricity demand for lighting and appliance, respectively. [9]

2.2.2.5. Reference systems

To show energy saving effect of advanced building service systems, three types of existing building service systems are taken as reference systems (Fig 2.2.6). Settings for lighting, household appliances and domestic hot water are the same among these systems. Space heating and cooling are supplied in different ways.

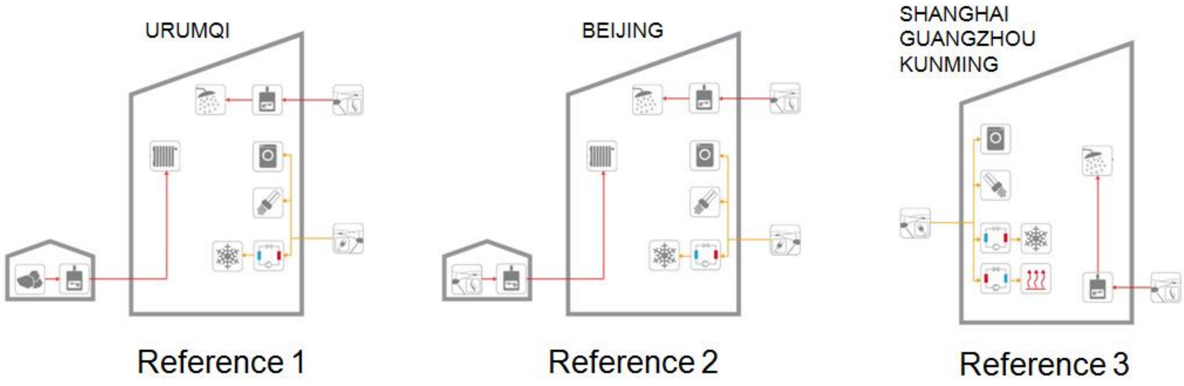


Fig 2.2.6 Reference systems

Reference 1 (Urumqi):
District heating (Coal-boiler), air-conditioner for cooling, small size gas water-heater for domestic hot water;
Reference 2 (Beijing):
District heating (Gas-boiler), air-conditioner for cooling, small size gas water-heater for domestic hot water;
Reference 3 (Shanghai, Guangzhou and Kunming):
Reversible air-conditioner for space heating and cooling, small size gas water-heater for domestic hot water

2.2.3. Energy Demand

2.2.3.1. Yearly useful energy demand (Q_U)

Space heating / cooling demand
The basic model is built and simulated in software "DesignBuilder". 18℃ and 26℃ are set-point temperature for space heating and cooling, respectively. Yearly useful energy demand could be shown as Fig 2.2.7.

Domestic hot water
According to "2011 annual report on China Building Energy efficiency", energy demand for domestic hot water in 2008 is 2.2 kgce / (m^2a). In this thesis, 18 kWh / (m^2a) is supposed to be useful energy demand for domestic hot water in each city.

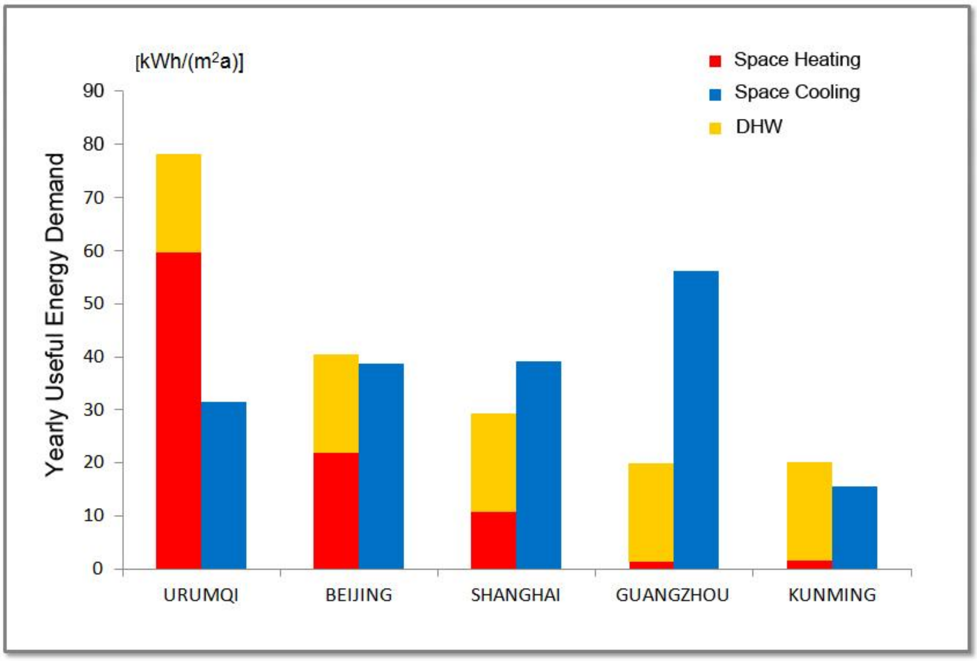


Fig 2.2.7 Yearly useful energy demand for space heating and cooling

Among these 5 cities, the highest heating demand and the highest cooling demand appear in Urumqi and Guangzhou, respectively. The basic model in Kunming has the lowest thermal energy demand. In Beijing and Shanghai, both heating and cooling demands have to be considered.

2.2.3.2. Final energy demand (Q_E)

Useful energy demands of basic model will be covered by building service systems. Considering the performance efficiency of reference systems, final energy demand in each city could be calculated.

$$Q_E = \frac{Q_U}{\eta_h} \quad \text{or} \quad Q_E = \frac{Q_U}{SPF}$$

Q_U = yearly useful energy demand [kWh / (m^2a)]
Q_E = yearly final energy demand [kWh / (m^2a)]
η_h = efficiency of heating system [-]
SPF = seasonal performance factor [-]

Take thermal energy demand in Urumqi as an example. According to simulation results (Fig 2.2.7), yearly useful energy demand for space heating (Q_{Uh}) and cooling (Q_{Uc}) are 60 kWh / (m^2a) and 31 kWh / (m^2a), respectively. Efficiency of space heating system (η_h) is 0.7 (coal-boiler), while efficiency of domestic hot water system ($\eta_{h\text{-}DHW}$) is 0.9 (gas-boiler). Seasonal performance factor of space cooling system (split air handling unit) is 2.3. Based on these data, yearly final energy demand of space heating (Q_{Eh}), space cooling (Q_{Ec}) and domestic hot water (Q_{Ed}) could be calculated as follow.

$$Q_{Eh} = \frac{Q_{Uh}}{\eta_h} = \frac{60}{0.7} = 86 \quad [\text{kWh/(m}^2\text{a)}]$$

$$Q_{Ec} = \frac{Q_{Uc}}{SPF_c} = \frac{31}{2.3} = 14 \quad [\text{kWh/(m}^2\text{a)}]$$

$$Q_{Ed} = \frac{Q_{Ud}}{\eta_{h-DHW}} = \frac{18}{0.9} = 20 \quad [\text{kWh/(m}^2\text{a)}]$$

Electricity demand of lighting and appliances are constant values in this thesis, which are 5.32 kWh/ (m^2a) and 5.11 kWh/ (m^2a) respectively. [9]

final energy (Q_E) [kWh/(m^2a)]	Space Heating (Q_{Eh})	Space Cooling (Q_{Ec}) SPF_c = 2.3	Domestic hot water (Q_{Ed}) η_{h-DHW} = 0.9	Lighting (Q_{El})	Appliances (Q_{Ea})
	Coal / Gas / Electricity	Electricity	Gas	Electricity	Electricity
URUMQI	Coal, η_h = 0.7, Q_{Eh}=86	14	20	5.3	5.1
BEIJING	Gas, η_h = 0.9, Q_{Eh}=24	17	20	5.3	5.1
SHANGHAI	Electricity, SPF_h=1.9, Q_{Eh}=6	17	20	5.3	5.1
GUANGZHOU	Electricity, SPF_h=1.9, Q_{Eh}=0.7	24	20	5.3	5.1
KUNMING	Electricity, SPF_h=1.9, Q_{Eh}=0.8	7	20	5.3	5.1

Table 2.2.2 Final energy demand in each city

2.2.3.3. Primary energy demand (Q_P)

As discussed in Chapter 1.2, final energy demand could not be added together, because of different primary energy factor (PE). Primary energy demand could be calculated by final energy demand and PE-factor as follow.

$$Q_P = Q_E \times PE$$

Q_P = yearly primary energy demand [kWh / (m^2a)]
Q_E = yearly final energy demand [kWh / (m^2a)]
PE = primary energy factor [-]
(In this thesis, PE_{coal} = 1.2, PE_{gas} = 1.1 and $PE_{electricity}$ = 2.7)

Take energy demand in Urumqi as an example. Yearly primary energy demand could be calculated as follow.

Space heating: $Q_{Ph} = Q_{Eh} \times PE_{coal} = 86 \times 1.2 = 103$ [kWh / (m^{2}a)]

Space cooling: $Q_{Pc} = Q_{Ec} \times PE_{electricity} = 14 \times 2.7 = 37.8$ [kWh / (m^{2}a)]

DHW: $Q_{Pd} = Q_{Ed} \times PE_{gas} = 20 \times 1.1 = 22$ [kWh / (m^{2}a)]

Lighting: $Q_{Pl} = Q_{El} \times PE_{electricity} = 5.3 \times 2.7 = 14.3$ [kWh / (m^{2}a)]

Appliances: $Q_{Pa} = Q_{Ea} \times PE_{electricity} = 5.1 \times 2.7 = 13.8$ [kWh / (m^{2}a)]

Total: $Q_P = Q_{Ph} + Q_{Pc} + Q_{Pd} + Q_{Pl} + Q_{Pa} = 191$ [kWh / (m^{2}a)]

As shown in Fig 2.2.8, yearly primary energy demand in Urumqi is the highest. It is nearly three times of that in Kunming, which is only 70 kWh/ (m^{2}a).

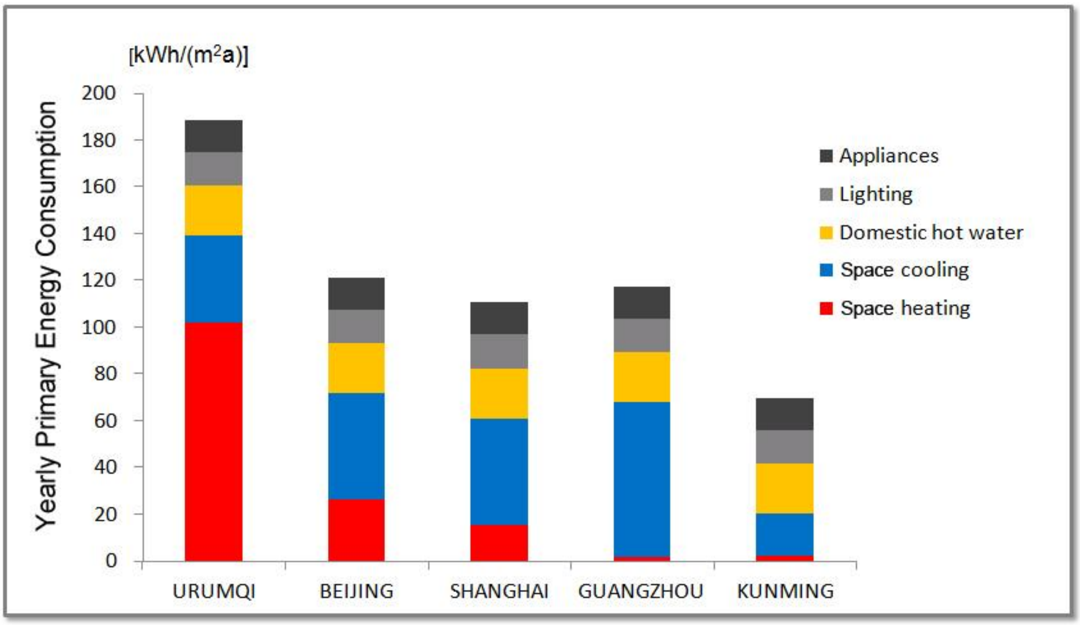


Fig 2.2.8 Yearly primary energy demand in each city

2.2.3.4. Slab-style VS Point-style

Besides Slab-style, point-style multi-story residential building is also popular in China. Fig 2.2.9 shows floor plan of slab-style and point-style. In point-style design, public space (including lifts and corridors) is surrounded by apartments as a core. The model of point-style multi-story residential building is also simulated in DesignBuilder. As shown in Fig 2.2.10, it is an 18 floor building. There are 6 apartments on each floor. Floor area of each apartment is $100m^2$. Window-to-wall ratio is 30% on each external wall. Double Clear glazing (6mm+13mm air+6mm) is the glazing type. All other settings are the same as slab-style model.

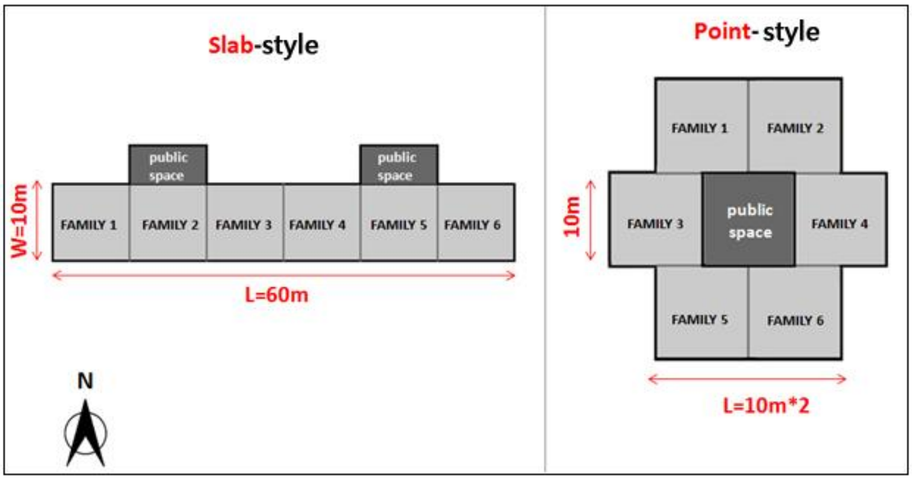


Fig 2.2.9 Floor plan of slab-style (left) and point-style (right)

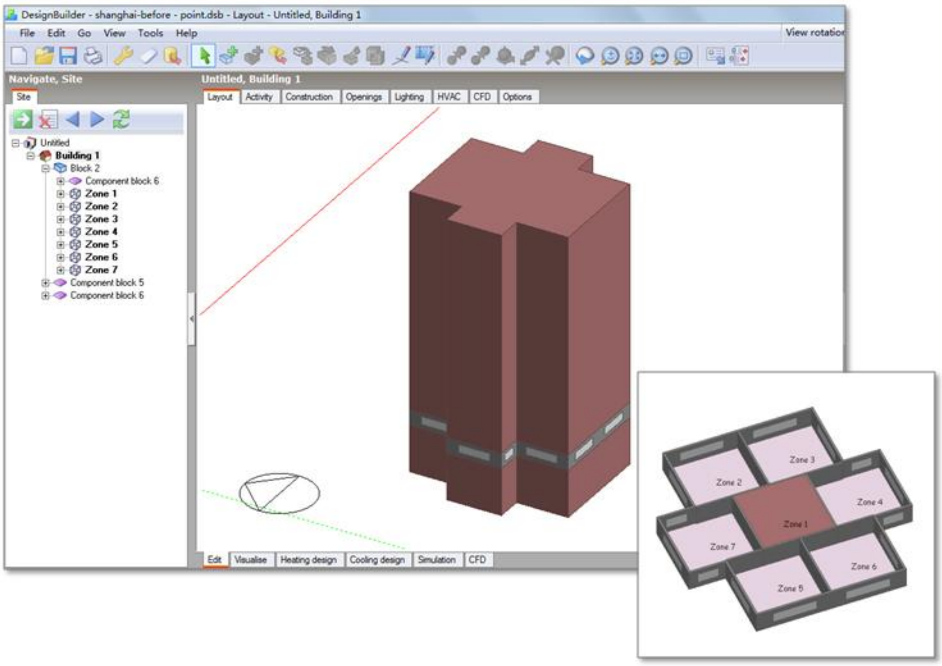


Fig 2.2.10 Point-style model in software “DesignBuilder”

According to the simulation in DesignBuiler, difference of thermal energy demand between slab-style and point-style is less than 7% (Fig 2.2.11). In the context of energy demand, slab-style and point-style are similar in each city.

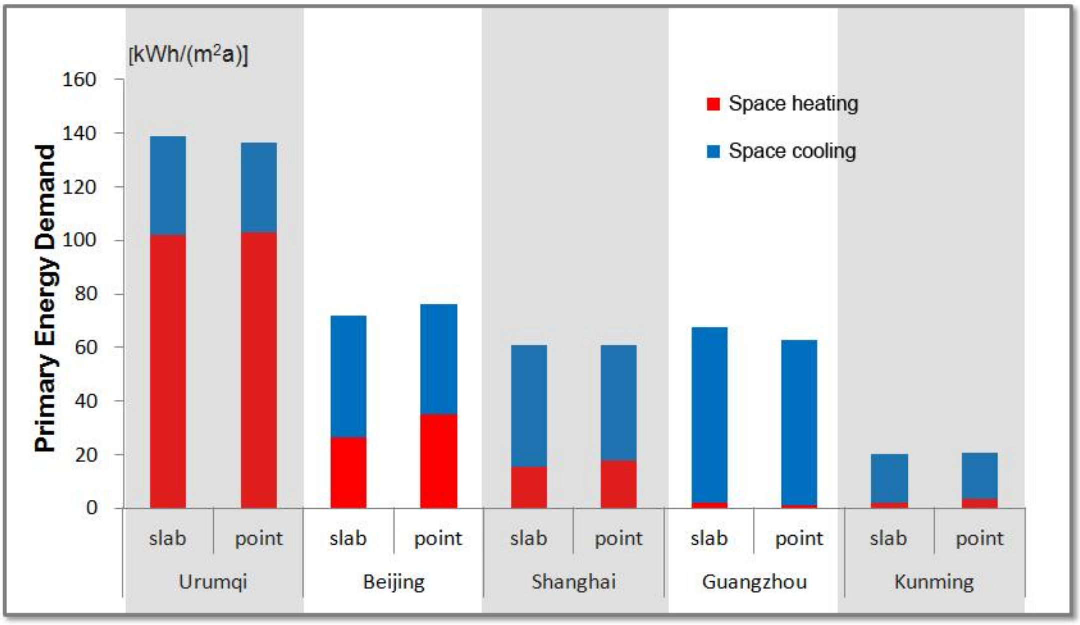


Fig 2.2.11 Yearly energy demands of Slab-style and Point-style

Chapter 3

LITERATURE REWIEW

3.1. Development of energy efficient residential buildings

3.1.1. Energy Concepts

Since energy crisis in 1970s, concerns about the building energy consumption have been growing in developed countries. Lots of concepts on building energy efficiency emerged. Germany is a good example to show the concept development of energy efficient residential buildings.

3.1.1.1. Low-energy House

In Europe, “Low-energy house” generally refers to a house with low energy consumption for space heating, which is about half of low-energy standards in Germany or Swiss. Energy consumption in “Ultra-low-energy building” could be even lower.

In Germany, yearly heating demand of “Low-energy house” (Niedrigenergiehaus) should be 50% lower than the level in WSVO (Wärmeschutzverordnung) 1982. It should be 25%~30% lower than the level in WSVO 1995. [10]

3.1.1.2. KfW-Efficient House

"KfW-Efficient House standard" was developed in 2009 by the KfW Promotional Banks in collaboration with the BMVBS and the German Energy Agency (dena). [3] It becomes the most important German program for enhancing building energy efficiency. Yearly primary energy demand of residential building is compared with the reference building, which is defined in EnEV (Energieeinsparverordnung). Table 3.1.1 shows the requirements of KfW-Efficient House Standard.

KfW-Efficient House	KfW 115	KfW 100	KfW 85	KfW 70	KfW 55	KfW 40
	Relating to reference building of valid EnEV					
Yearly primary energy demand (Q_P)	115%	100%	85%	70%	55%	40%
Transmission heat loss (H_T')	130%	115%	100%	85%	70%	55%

Table 3.1.1 Requirements of KfW-Efficient House Standard

Take "KfW 70" as an example. Yearly primary energy demand of this building is less than 70% of reference building. Transmission heat-loss in such building is not more than 85% of that in reference building.

3.1.1.3. Passive and Active Solar House

There are two main types of solar energy using, which are passive solar house and active solar house. In passive solar house, building components are used to collect, store, and distribute solar energy in the form of heat in the winter and reject solar heat in the summer. Large glazing area, greenhouse and thermal mass are main characteristics. No mechanical and electrical devices are involved in this process.

Fig 3.1.1 Passive solar house Landstuhl (Germany)

(Picture source: M.Norbert Fisch, Thomas Wilken, Christina Stähr. Energie PLUS)

Researches on passive solar house in Germany started from 1970s. From 1979 to 1989, twenty-two single-family houses and three reference buildings were built as demonstration project “Solar houses Landstuhl”. However, compared with reference buildings, the heat losses from large insulating glass surfaces (double glazing) were not compensated by the useful solar energy gains under the condition of technology in that age. [3]

Compared with passive-solar house, active solar house is more depending on mechanical and electrical devices. They catch solar energy and convert it into another energy form (heat or electricity). Solar thermal system and solar photovoltaic system are two popular types of them. In solar thermal systems, solar energy is collected by solar collectors and converted into heat. It could be saved in storage for later use. Combined with an absorption chiller, solar thermal system could also afford solar cooling in summer. In solar photovoltaic system, solar energy is converted into electricity by PV module. This electricity could be used in building to cover its own electricity demand. It is also possible to feedback electricity grid and change the building into a small power station.

3.1.1.4. Passive House (PH)

Yearly heating demand of a building, which is labeled as “Passive House”, should be lower than 15kWh/(m^2a). Additionally, the total primary energy demand should be lower than 120 kWh/(m^2a). The first PH was developed at IWU in Darmstadt by Dr. Wolfgang Feist and was built in 1991 in Darmstadt-Kranichstein. Until now, there is no legal standard for Passive House. PHPP Standard is used to prove the energy quality of Passive House.

Fig 3.1.2 Passive House in Darmstadt-Kranichstein

(Picture source: M.Norbert Fisch, Thomas Wilken, Christina Stähr. Energie PLUS)

3.1.1.5. Zero energy House

When total energy demand could be 100% covered by renewable energy (such as passive / active solar thermal energy) and no additional energy source is needed, this house could be labeled as “Zero energy House”. The first zero energy house was founded in 1997 in Berlin. Theoretically, yearly energy demand of space heating and domestic hot water could be fully covered by active solar energy. No additional energy is needed in this building. However, it is not possible in practice because of the lag between solar supply and heating demand [3]. On the other hand, it is impossible to keep a building in exact condition of “zero energy”. When energy generation is higher than consumption, it should be called as “Energy PLUS”.

Fig 3.1.3 Zero Energy House in Berlin

(Picture source: M.Norbert Fisch, Thomas Wilken, Christina Stähr. Energie PLUS)

3.1.1.6. Energy PLUS House

Plus-energy house concept (Plusenergiehaus®) was developed by the architect Rolf Disch in the early 1990s. In annual energy balance, when PV electricity feedback to the public grid is higher than its electricity demand getting from electricity grid, this house is defined as Energy PLUS house.

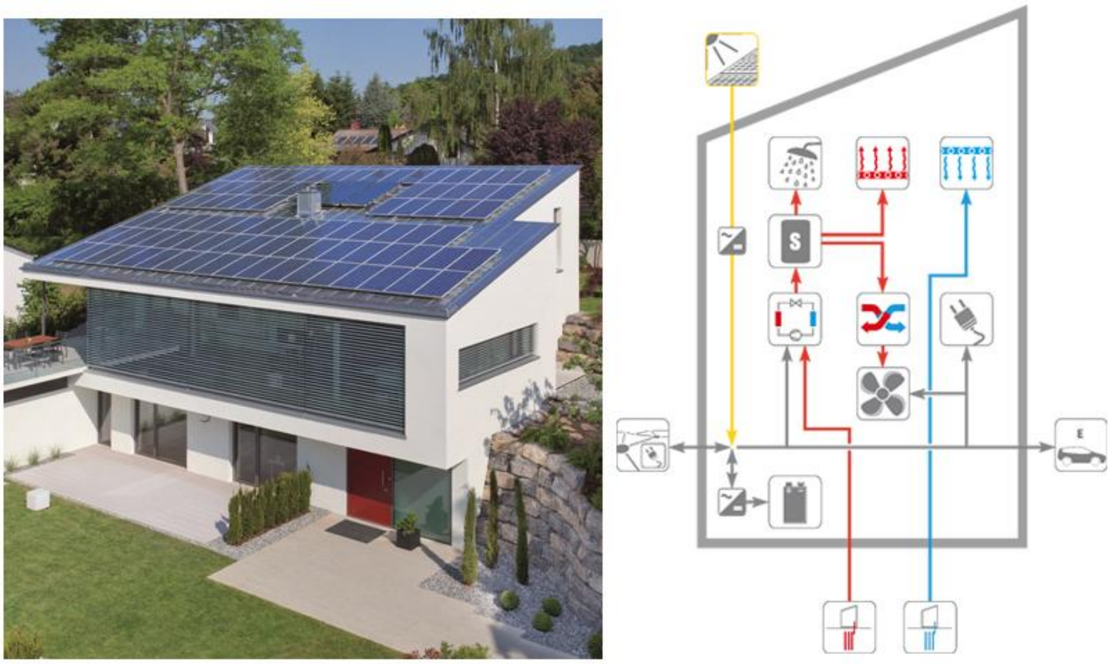


Fig 3.1.4 Energy PLUS House in Leonberg

(Picture source: M.Norbert Fisch, Thomas Wilken, Christina Stähr. Energie PLUS)

“Energy PLUS House in Leonberg” is a good example. It is a two-story residential building, which was built in 2010. Energy concept of this building is developed by Prof. Dr. Norbert M. Fisch. Due to the absence of natural gas and district heating on site, an “electricity house” concept was implemented. On the shed roof, a PV system (15 kW_P) was installed to generate electricity. Since the shutdown of solar thermal system (7 m^2 on the roof) in March 2011, heat is generated monovalently by the electric ground-coupled heat pump. According to monitoring results, the photoelectric yield in the first two years (2011/2012) are 16274 kWh/a (2011) and 15923 kWh/a (2012), respectively. It is approximately 180% (2011) and 144% (2012) of annual electricity consumption, which are 9027 kWh/a (2011) and 11060 kWh/a (2012). [3]

3.1.2. Laws and Standards

3.1.2.1. Germany

In Germany, the first heat protection directive (Wärmeschutzverordnung: WSVO) was published in1977 and revised in 1984. According to this code, heat transfer coefficients (U-value) of building construction were limited. In the revised version WSVO 1995, yearly heating demand is used as index. System thermal efficiency for providing space heating, domestic hot water, mechanical ventilation and the necessary auxiliary energy are not considered until EnEV 2002.

Energy Conservation Regulation (Energieeinsparverordnung: EnEV) was published in 2002. In EnEV 2002, the system’s thermal efficiency for providing space heating, domestic hot water, mechanical ventilation and the necessary auxiliary energy are considered. Heat produced by renewable energy and used in a building is also involved in energy balance. Yearly primary energy demand (Q_P) and heat-losses through the building envelope (H'_T) are considered as indexes. In EnEV 2009, the limited value of yearly primary energy demand is even lower. It is about 70 kWh/(m^2a) for space heating and domestic hot water together.

3.1.2.2. USA

Since late 1970s, energy conservation has been written in laws. The “Energy Policy and Conservation Act” was published in 1975. It is the first step towards a comprehensive and systematic federal energy policy. [11] “Resource Conservation and Recovery Act (1976)”, “National Energy Conservation Policy Act (1978)”and “Federal Energy Management Improvement Act (1988)” showed their concern on building energy efficiency. Between 1991 and 1998, ten Executive Orders were published to improve building energy efficiency. [12]

3.1.2.3. Japan

Energy Crisis gave a big hit to Japan in 1970s. “Energy Utilization Reasonability Law (EURL)” was published in 1979 as a positive response. It has been amended in 1992, 1999 and 2002. “Design and Construction Guidelines on the Rationalization of Energy Use for Houses” and “Criteria for Clients on the Rationalization of Energy Use for Houses” are valid Standards in residential field. They both published in 1980 and amended twice in 1992 and 1999. [13] In 2006, “Basic Program for Housing” was enacted by Ministry of Land, Infrastructure and Transport (MLIT). According to this program, energy saving standards will be more stringent from 2015.

3.1.2.4. China

Compared with developed countries, China has a late start in the field of energy efficient residential buildings. “Energy Conservation Standard for New Heating Residential Buildings (JGJ 26-86)”, which was enacted in 1986, was the first move. It was revised in 1995 (JGJ26-95).

After that, series of energy conversation standards were published. “Thermal design code for civil building (GB50176-93)” was enacted in 1993. Thermal resistance of external wall, Window-to-wall Ratio and air-tightness are limited. According to this standard, China is divided into 5 climate zones with different requirement for building design. After that, energy saving standards focusing on special climate zones were enacted, such as “Design Standard for energy efficiency of residential Buildings in Hot summer and cold winter zone (JGJ134-2001)” and “Design Standard for energy efficiency of residential Buildings in Hot summer and warm winter zone (JGJ75-2003)”.

In “Design Standard for energy efficiency of residential Buildings in Hot summer and cold winter zone (JGJ134-2001)”, reference building is defined. Energy demand of real building could be simulated and compared with reference building to show its energy efficiency. It is similar as EnEV in Germany. From then on, “reference building” started to be used in later Standards such as JGJ75-2003 and JGJ134-2010.

3.1.3. Practice in China

3.1.3.1. Ultra-low-energy demonstration building at Tsinghua University, Beijing

Demonstration building in Tsinghua is the first Ultra-low-energy building in China. It was built in Beijing in 2005 as a research project in the field of building energy efficiency. It is a 4-floor building with a basement. Total floor area is 3000m^2.

Fig 3.1.5 Ultra-low energy demonstration building at Tsinghua University, Beijing

(Picture source: http://www.archcy.com)

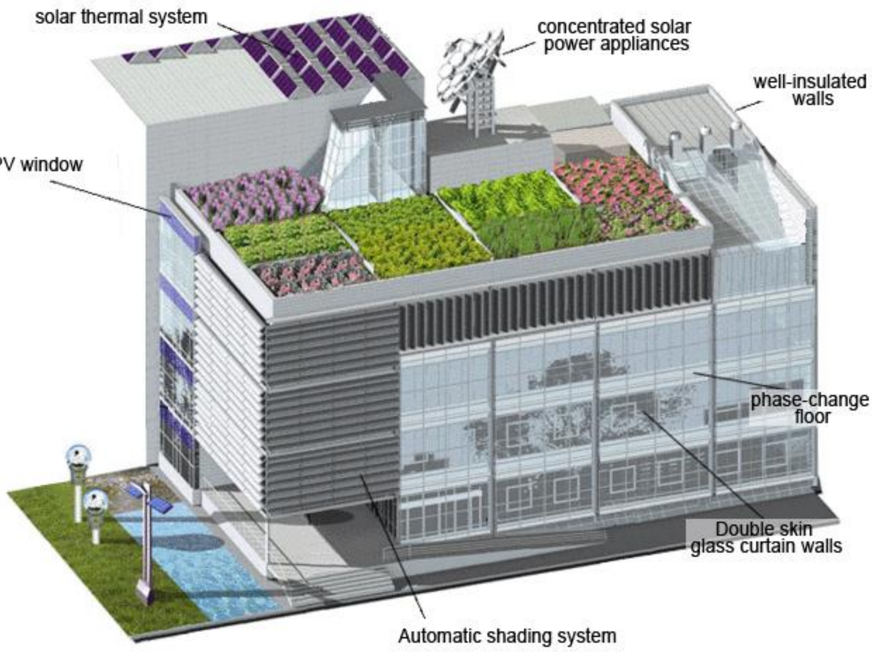


Fig 3.1.6 Energy strategies in Ultra-low energy demonstration building

(Picture source: http://www.baisi.net; Re-edited by the author)

Beijing locates in Cold climate zone in China. Thermal performance of building envelope in this project is very good. Insulation layer for western and northern wall is 300 mm thick. Heat transfer coefficient (U-value) of these external walls is 0.3 W/ (m^2K). Double skin glass curtain walls with automatic shading system are used on the south and east. U-value is 1.0 W/ (m^2K). Solar heat gain factor (g-value) is 0.5. All external windows are double glazing. Floors are made of phase-change materials (PCM), which could work as thermal mass.

"Building combined heating and power system (BCHP)" is used in this building. Fuel cells release heat when it generates electricity. This heat is saved in storage, which could also be charged by solar thermal system. Controlled mechanical ventilation system (CMV) is combined with solution dehumidification system. Heat recovery rate of controlled mechanical ventilation system is higher than 80%. Solar absorption chiller and electric chiller combined with radiant ceiling are used as cooling system. Besides BCHP, 30m^2 PV windows on southern wall and 3 kW concentrated solar power appliances with dual axis solar tracker on the roof could also generate electricity.

According to simulation results [14], average heat load in winter is 0.7 W/m^2. Even in the coldest month, the heat load is only 2.3W/m^2. In the hottest month, heat-gain of building envelope is 5.2 W/m^2. Yearly electricity demand is 40 kWh / (m^{2}a) including lighting and appliances. It is about 30% of average electricity consumption in office buildings in Beijing.

3.1.3.2. Pujiang Intelligence Village Office Building, Shanghai

"Pujiang Intelligence Valley Office Building" is awarded the first Energy Performance Certificate (Chapter 3.2.1) for Chinese buildings in 2006. It was built in Shanghai, which locates in hot summer and cold winter zone. Two towers (7 floors of each) are connected together at the first and second floor. Floor area of this building is about 12000 m^2.

Fig 3.1.7 Pujiang Intelligence Valley Office Building

(Picture source: http://www.shzfrx.com)

Envelope of this building is well insulated. Heat transfer coefficient of external wall (U_{wall}) and roof (U_{roof}) are only 0.4 W/ (m ·K). Double Low-E glazing with shading blinds is designed for external windows. In this building, ground-coupled heat pump system supplies space heating in winter. It could also cover part of cooling demand in summer. As shown in Energy Performance Certificate (Fig 3.1.8), primary energy demand of overall system (including space heating, space cooling, domestic hot water, lighting and ventilation) is 250 kWh / (m^{2}a). It is about 30% of that in normal Chinese office buildings (with air-conditioner). This value is even lower than that in middle Europe.

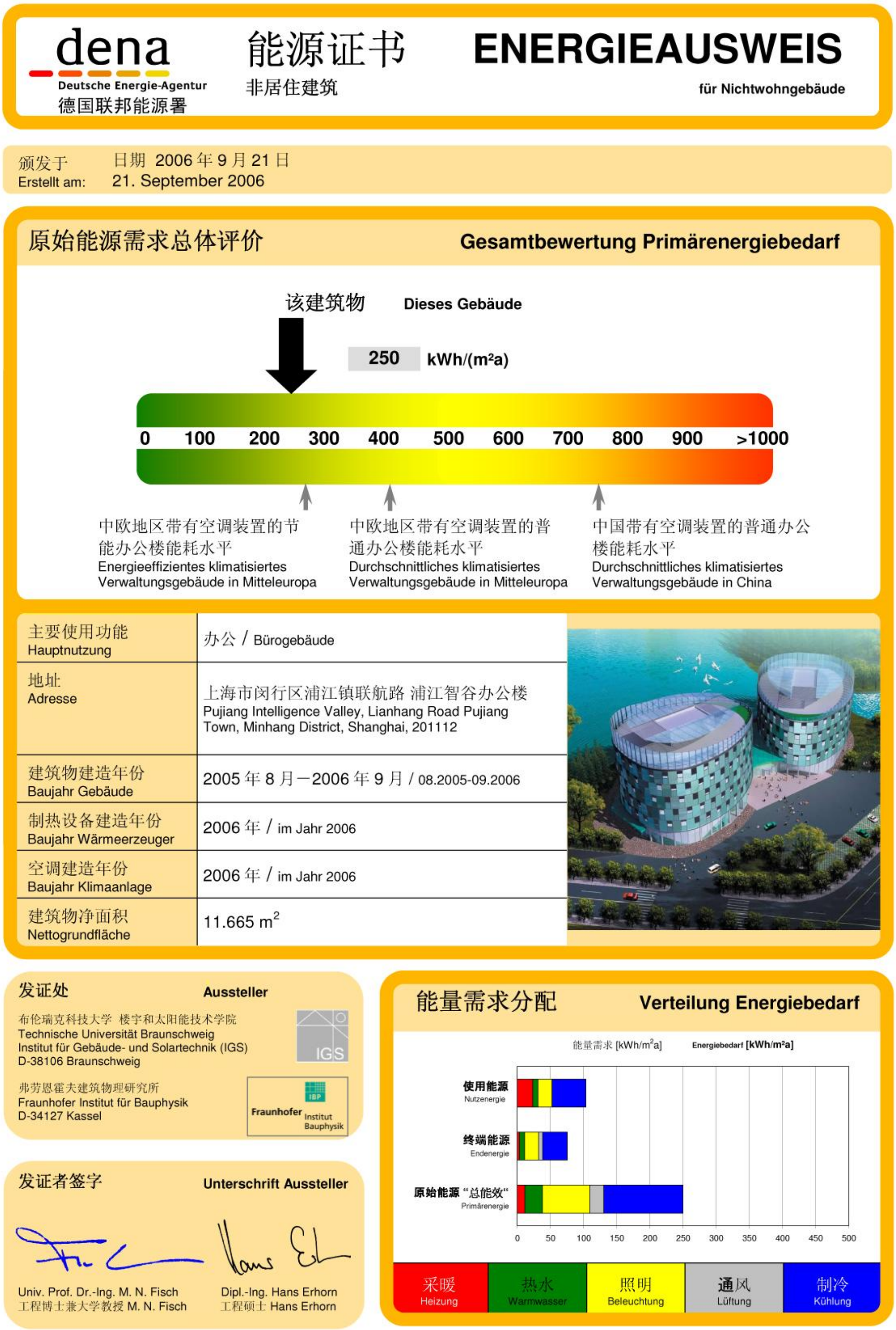


Fig 3.1.8 The first Energy Performance Certificate in China

(Picture source: Institut für Gebäude- und Solartechnik, TU Braunschweig)

3.1.3.3. Nanjing Chengkai Yuyuan, Nanjing

The first Energy Performance Certificate (Energieausweis) for Chinese residential building is awarded to the project “Nanjing Chengkai Yuyuan” in 2009. This project consists of 8 residential buildings. Total floor area is about 31000 m^2.

Fig 3.1.9 Nanjing Chengkai Yuyuan - the first Energy Performance Certificate for residential buildings
(Picture source: (left) http://www.cnkg.com.cn; (right): http://epaper.yangtse.com)

This project “Chengkai Yuyuan” locates in Nanjing, which belongs to hot summer and cold winter climate zone in China. In this project, building envelope is well-insulated. Space heating and cooling are served by the combination of ground-coupled heat pump system, solar thermal system and capillary tube radiation system. Controlled mechanical ventilation system (CMV) supplies fresh air and improves indoor comfort. According to the Energy Performance Certificate, yearly primary energy demand in this project could be about 60 kWh / (m^2a).

3.1.3.4. Passive House in Qinhuangdao, Hebei

The project “Water Front” is co-operated by Chinese and German experts in the field of energy efficiency. Residential building “C12” is built as the first “passive house” demonstration building in China. There are 36 flats on 18 floors. The total floor area is about 6500 m^2. It started from March 2012, and supposed to be finished until October 2013.

Fig 3.1.10 Residential building “C12”

(Picture source: http://www.dena.de)

Fig 3.1.11 Energy strategies in residential building C12

(Picture source: http://www.zaishuiyifang.cn; Re-edited by the author)

This project locates in Qinhuangdao, which belongs to cold climate zone in China. Thermal performance of building envelope in this project is excellent. Insulation layer of external wall is 220 mm EPS (WLG 030). Heat transfer coefficient (U-value) of these external walls is 0.13 W/ (m^2K). Roofs and floors are also well-insulated. Heat transfer coefficient (U-value) of roof and floor are 0.10 W/ (m^2K) and 0.12 W/ (m^2K), respectively. External windows are triple glazing and vacuum glazing. U-value of external window is 0.8W/ (m^2K). According to test, air-tightness of this building is satisfied (n_{50} = 0.2 ~ 0.4 /h).

Reversible air-conditioner supplies space heating, cooling and mechanical ventilation. Heat in the exhaust air is recovered by air-source heat pump. Heat recovery rate of mechanical ventilation is 70%~80%. Domestic hot water is supplied by solar thermal system. Solar collectors are installed on the veranda fence. Besides solar thermal system, recovered heat is also used to supply domestic hot water in summer.

According to simulation results from German Energy Agency (dena), primary energy demand for heating and cooling in this building is only 16 kWh/ (m^2a). Total primary energy demand is 102 kWh/ (m^2a), which is lower than the limit value “120 kWh/ (m^2a)” for passive house.

3.2. Rating system of energy efficient buildings

3.2.1. Energy Performance Certificate (Energieausweis) in Germany

In order to make energy performance of a building more transparent to its tenants, purchasers and owners, Energy Performance Certificate (Energieausweis) is developed by German Energy Agency (DENA). It has already been written in EnEV. An Energy Performance Certificate is necessary for the rental, sale and leasing of houses and flats since 1 January 2009. Energy Performance Certificate is valid for 10 years.

There are two types of Energy Certificates, which are Demand Certificate (Bedarfsausweis) and Usage Certificate (Verbrauchsausweis), respectively. In Demand Certificate (Bedarfsausweise), primary energy demand and final energy demand are indicated; in Usage Certificate (Verbrauchsausweis), only final energy consumption is shown. Demand Certificate is necessary for new buildings, while Usage certificate could also be available for existing buildings depending on the building size and age. For big buildings (more than 4 families) and old small buildings (built before 1977 and fulfills requirements in WSVO1977), both certificates are available.

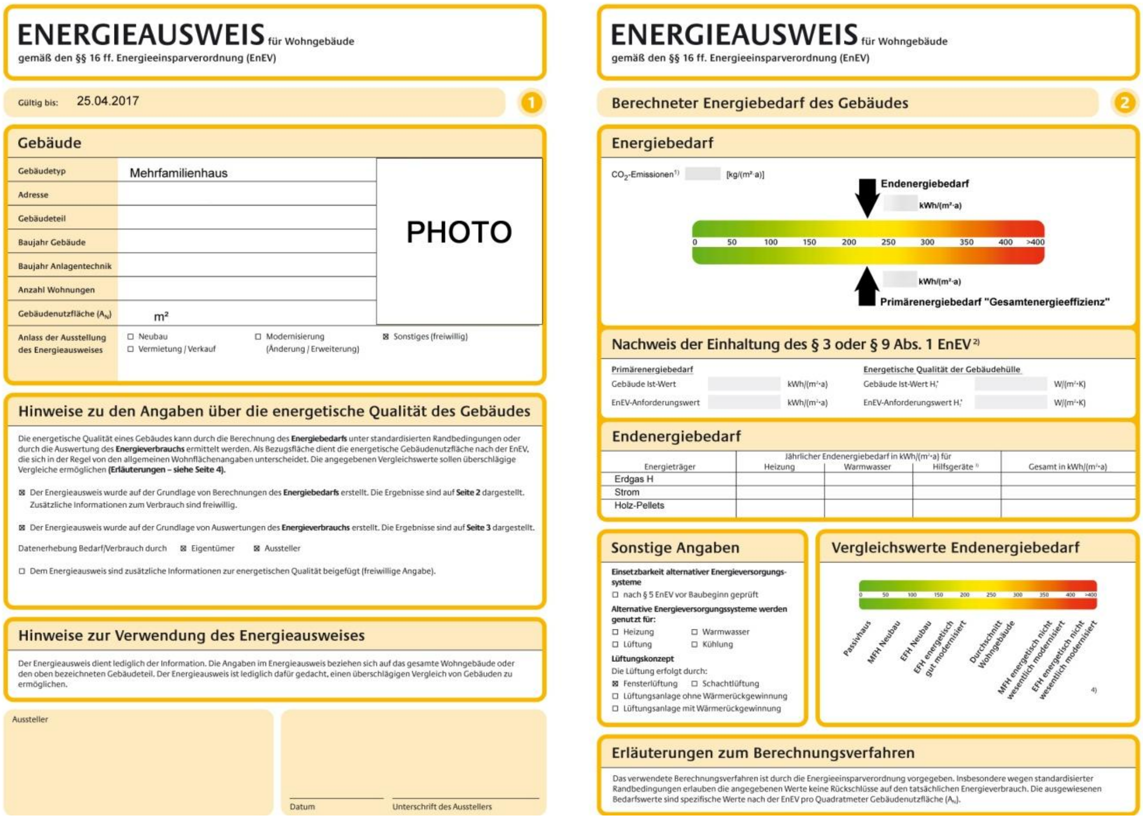
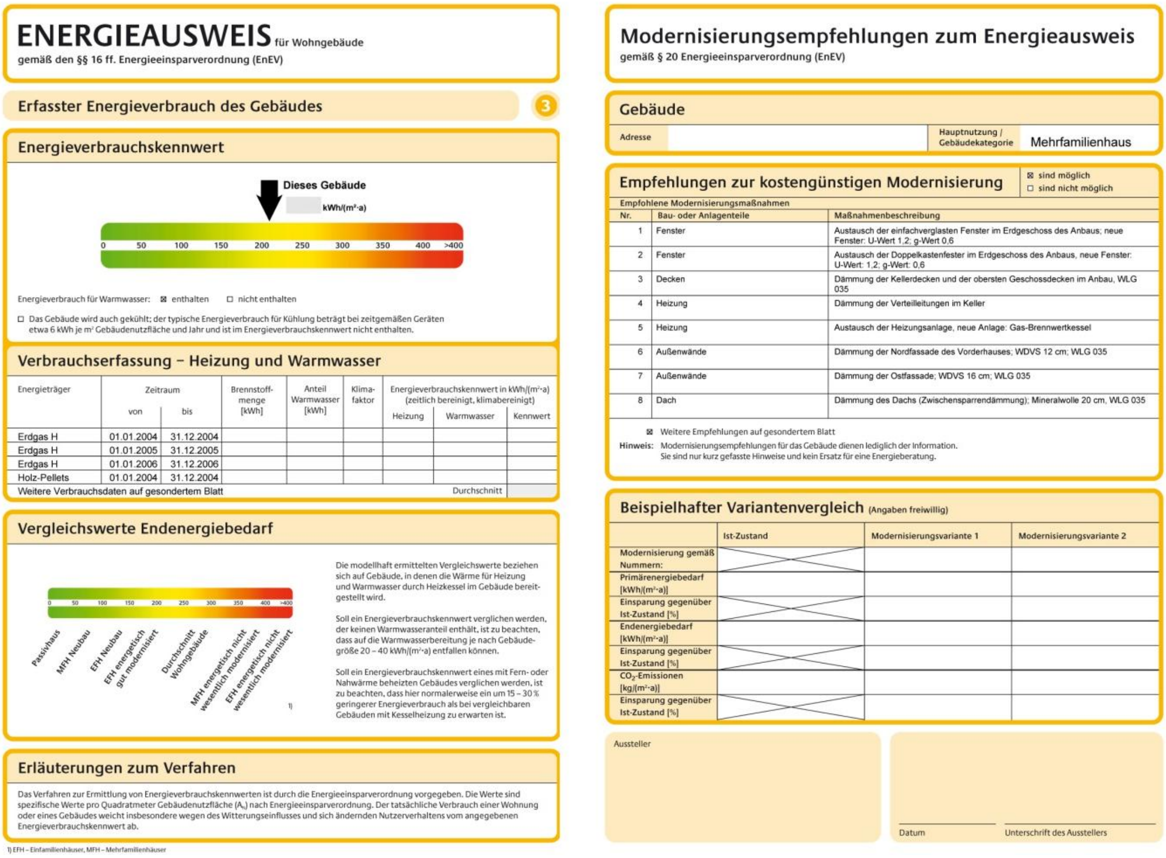


Fig 3.2.1 First two pages of Energy Performance Certificate (Energieausweis)

Here is an example of Energy Performance Certificate for a residential building. The first page is basic information about the building, such as type, location, construction time and floor area. On the second page, yearly final energy demand and primary energy demand which calculated according to EnEV 2009 are shown on the top. On the bottom of page 2, there is a reference card. Building energy performance is classified by its final energy demand. According to this card, it is easy to know the energy performance of a residential building.



ENERGIEAUSWEIS für Wohngebäude
gemäß den §§ 16 ff. Energieeinsparverordnung (EnEV)

Erfasster Energieverbrauch des Gebäudes 3

Energieverbrauchskennwert

Dieses Gebäude
kWh/(m²·a)

0 50 100 150 200 250 300 350 400 >400

Energieverbrauch für Warmwasser: ☒ enthalten ☐ nicht enthalten

☐ Das Gebäude wird auch gekühlt; der typische Energieverbrauch für Kühlung beträgt bei zeitgemäßen Geräten etwa 6 kWh je m² Gebäudenutzfläche und Jahr und ist im Energieverbrauchskennwert nicht enthalten.

Verbrauchserfassung – Heizung und Warmwasser

Energieträger	Zeitraum von	Zeitraum bis	Brennstoff-menge [kWh]	Anteil Warmwasser [kWh]	Klima-faktor	Energieverbrauchskennwert in kWh/(m²·a) (zeitlich bereinigt, klimabereinigt) Heizung	Warmwasser	Kennwert
Erdgas H	01.01.2004	31.12.2004						
Erdgas H	01.01.2005	31.12.2005						
Erdgas H	01.01.2006	31.12.2006						
Holz-Pellets	01.01.2004	31.12.2004						
Weitere Verbrauchsdaten auf gesondertem Blatt							Durchschnitt	

Vergleichswerte Endenergiebedarf

Die modellhaft ermittelten Vergleichswerte beziehen sich auf Gebäude, in denen die Wärme für Heizung und Warmwasser durch Heizkessel im Gebäude bereitgestellt wird.

Soll ein Energieverbrauchskennwert verglichen werden, der keinen Warmwasseranteil enthält, ist zu beachten, dass auf die Warmwasserbereitung je nach Gebäudegröße 20 – 40 kWh/(m²·a) entfallen können.

Soll ein Energieverbrauchskennwert eines mit Fern- oder Nahwärme beheizten Gebäudes verglichen werden, ist zu beachten, dass hier normalerweise ein um 15 – 30 % geringerer Energieverbrauch als bei vergleichbaren Gebäuden mit Kesselheizung zu erwarten ist.

Erläuterungen zum Verfahren

Das Verfahren zur Ermittlung von Energieverbrauchskennwerten ist durch die Energieeinsparverordnung vorgegeben. Die Werte sind spezifische Werte pro Quadratmeter Gebäudenutzfläche (A_N) nach Energieeinsparverordnung. Der tatsächliche Verbrauch einer Wohnung oder eines Gebäudes weicht insbesondere wegen des Witterungseinflusses und sich ändernden Nutzerverhaltens vom angegebenen Energieverbrauchskennwert ab.

1) EFH – Einfamilienhäuser, MFH – Mehrfamilienhäuser

Modernisierungsempfehlungen zum Energieausweis
gemäß § 20 Energieeinsparverordnung (EnEV)

Gebäude

Adresse		Hauptnutzung / Gebäudekategorie	Mehrfamilienhaus

Empfehlungen zur kostengünstigen Modernisierung ☒ sind möglich ☐ sind nicht möglich

Empfohlene Modernisierungsmaßnahmen

Nr.	Bau- oder Anlagenteile	Maßnahmenbeschreibung
1	Fenster	Austausch der einfachverglasten Fenster im Erdgeschoss des Anbaus; neue Fenster: U-Wert 1,2; g-Wert 0,6
2	Fenster	Austausch der Doppelkastenfester im Erdgeschoss des Anbaus, neue Fenster: U-Wert: 1,2; g-Wert: 0,6
3	Decken	Dämmung der Kellerdecken und der obersten Geschossdecken im Anbau, WLG 035
4	Heizung	Dämmung der Verteilleitungen im Keller
5	Heizung	Austausch der Heizungsanlage, neue Anlage: Gas-Brennwertkessel
6	Außenwände	Dämmung der Nordfassade des Vorderhauses; WDVS 12 cm; WLG 035
7	Außenwände	Dämmung der Ostfassade; WDVS 16 cm; WLG 035
8	Dach	Dämmung des Dachs (Zwischensparrendämmung); Mineralwolle 20 cm, WLG 035

☒ Weitere Empfehlungen auf gesondertem Blatt

Hinweis: Modernisierungsempfehlungen für das Gebäude dienen lediglich der Information. Sie sind nur kurz gefasste Hinweise und kein Ersatz für eine Energieberatung.

Beispielhafter Variantenvergleich (Angaben freiwillig)

	Ist-Zustand	Modernisierungsvariante 1	Modernisierungsvariante 2
Modernisierung gemäß Nummern:			
Primärenergiebedarf [kWh/(m²·a)]			
Einsparung gegenüber Ist-Zustand [%]			
Endenergiebedarf [kWh/(m²·a)]			
Einsparung gegenüber Ist-Zustand [%]			
CO_2-Emissionen [kg/(m²·a)]			
Einsparung gegenüber Ist-Zustand [%]			

Aussteller

Datum

Unterschrift des Ausstellers

Fig 3.2.2 Usage Certificate (left) and Suggestions (right)

Usage Certificate (Verbrauchsausweis) indicates energy consumption of real building. Average yearly final energy consumption in last three years is shown. It will be compared with the reference card on the bottom to show the real energy performance of the building.

With the help of Energy Performance Certificate, building energy performance is transparent to its tenants, purchasers and owners. Suggestions about improving building energy efficiency could also be given based on these results. It is helpful in the process of building design and renovation.

Fig 3.2.3 “Pujiang Intelligence Village office building” (left) and “Nanjing Chengkai Yuyuan” (right)

Energy Performance Certificate has already been introduced into China. The project “Pujiang Intelligence Village Office Building” (Chapter 3.1.3.2) in Shanghai received the first Energy Performance Certificate for office building in 2006. The first Energy Performance Certificate for residential building was awarded to the project “Nanjing Chengkai Yuyuan” (Chapter 3.1.3.3) in 2009.

3.2.2. Home Energy Rating System (HERS) in the USA

As introduced on its website (http://www.resnet.us), the Home Energy Rating System (HERS) Index is “the nationally recognized scoring system for measuring a home’s energy performance” in the USA. It was created and developed by RESNET (Residential Energy Services Network). As similar as Energy Performance Certificate (Germany), HERS Index makes energy efficiency of houses transparent to homeowners and buyers.

RESNET HERS INDEX

Fig 3.2.4 Logo of HERS Index

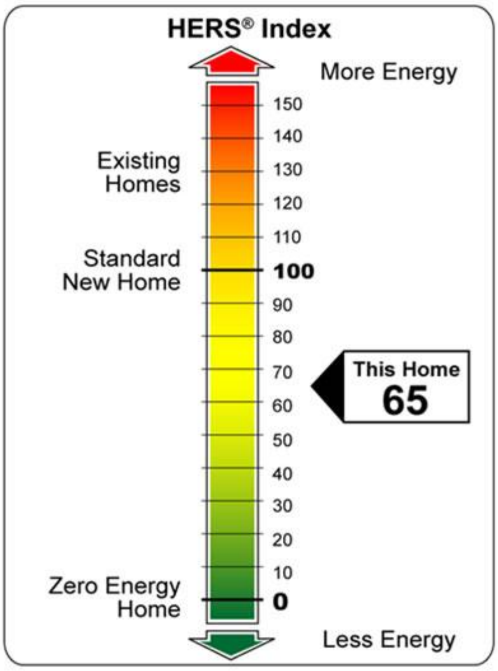


Fig 3.2.5 Home Energy Rating System (HERS) Index
(Picture source: http://www.resnet.us)

To calculate a home’s HERS Index Score, a certified RESNET home energy rater carries out an energy rating on people’s home and compares the data against the “Reference home”. A HERS Index score is generated based upon the results of the rating. The U.S. Department of Energy has determined that a standard new home is awarded a rating of 100 on the HERS Index. A home with a HERS Index Score of 70 is 30% more energy efficient than a standard new home.

3.2.3. Nationwide House Energy Rating Scheme (NatHERS) in Australia

House Energy Rating Index indicates building's thermal performance for residential buildings in Australia. Energy consumption for domestic hot water, lighting and household appliances are not included in this rating system.

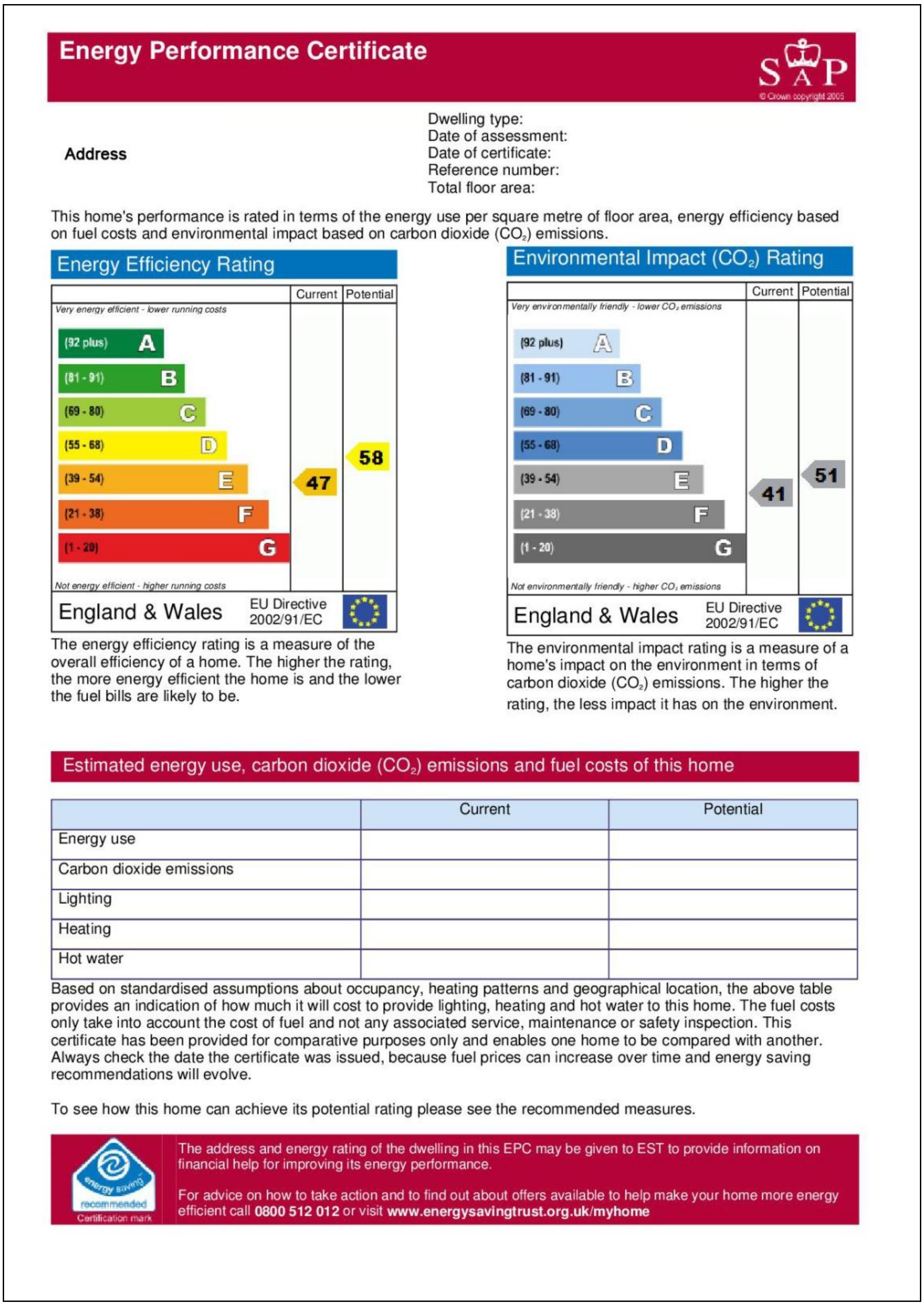
Fig 3.2.6 Logo of NatHERS (Picture source: http://nathers.gov.au)

Through Nationwide House Energy Rating Scheme (NatHERS), a scale of zero to 10 stars is used to assess the potential thermal comfort of Australian homes. This rating system bases on computer simulation results. The house with more stars means it has better thermal performance. In this rating scheme, building service technology is not considered.

3.2.4. Energy Performance Certificates (EPC) in UK

Energy Performance Certificates (EPC) for homes was first introduced in 2007 as part of home information packs (Hips). Hips were scrapped in 2010, but EPC is still required when renting, selling and buying a residential building in UK. EPC could only be produced by a Domestic Energy Assessor, who has already been accredited.

The rating scale of EPC is from A (most efficient) to G (least efficient). It is valid for 10 years. Here is an example of EPC (Fig 3.2.7). The Energy Efficiency Rating and Environmental Impact (CO_2) Rating will be indicated. Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs are compared with the potential value. Recommendations on improving building energy performance will be given as a part of this certificate.



Energy Performance Certificate

SAP

© Crown copyright 2005

Address

Dwelling type:
Date of assessment:
Date of certificate:
Reference number:
Total floor area:

This home's performance is rated in terms of the energy use per square metre of floor area, energy efficiency based on fuel costs and environmental impact based on carbon dioxide (CO_2) emissions.

The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating, the more energy efficient the home is and the lower the fuel bills are likely to be.

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating, the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

	Current	Potential
Energy use		
Carbon dioxide emissions		
Lighting		
Heating		
Hot water		

Based on standardised assumptions about occupancy, heating patterns and geographical location, the above table provides an indication of how much it will cost to provide lighting, heating and hot water to this home. The fuel costs only take into account the cost of fuel and not any associated service, maintenance or safety inspection. This certificate has been provided for comparative purposes only and enables one home to be compared with another. Always check the date the certificate was issued, because fuel prices can increase over time and energy saving recommendations will evolve.

To see how this home can achieve its potential rating please see the recommended measures.

energy saving recommended
Certification mark

The address and energy rating of the dwelling in this EPC may be given to EST to provide information on financial help for improving its energy performance.

For advice on how to take action and to find out about offers available to help make your home more energy efficient call **0800 512 012** or visit **www.energysavingtrust.org.uk/myhome**

Fig 3.2.7 Energy Performance Certificates (EPC) in UK

3.3. Advanced building service technology

3.3.1. Solar thermal technology

Principle of solar thermal system is collecting solar energy and changes it into heat. According to the temperature, solar thermal systems could be divided into 3 types. “Low-temperature solar thermal system” usually works for swimming pool heating and ventilation air preheating. Its temperature is under 30℃. “Medium-temperature solar thermal system” is used for domestic hot water heating and space heating. Its temperature is 30℃~100℃. “High-temperature solar thermal system” is suitable for industrial process heating and electricity generation. Its temperature is over 100℃. In this thesis, only “Medium-temperature solar thermal system” is discussed.

In residential buildings, solar thermal system could supply domestic hot water and space heating. Solar heating system consists of three main components, which are solar collector, heat storage and control equipment. Absorption chiller could be driven by solar heat. With help of absorption chiller, solar thermal system could be used for space cooling.

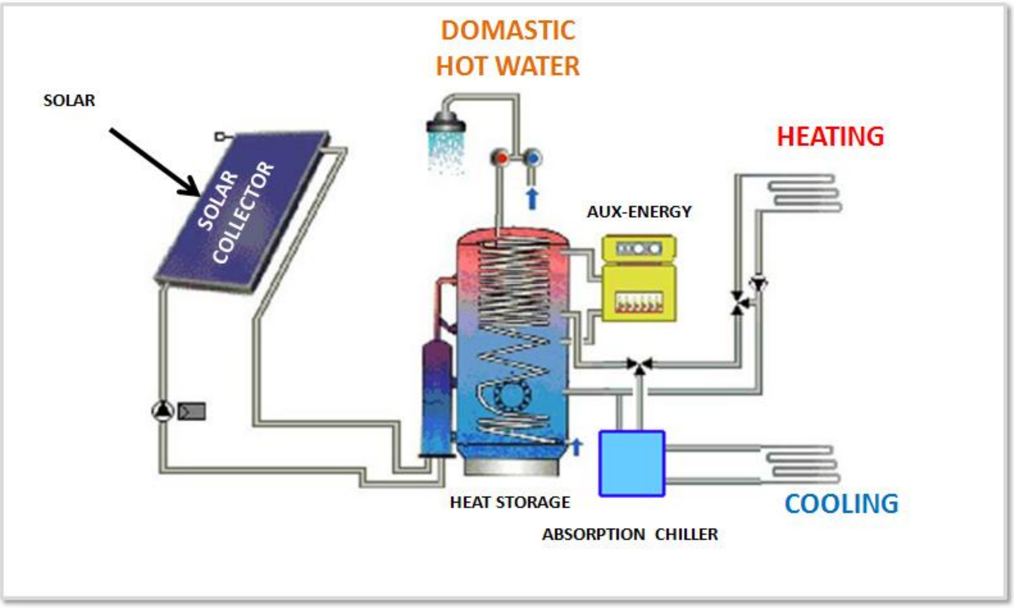


Fig 3.3.1 Solar thermal system – Heating, DHW and Cooling

Solar collector is the most important component in solar thermal system. There are kinds of solar collector used in solar thermal systems, such as “unglazed solar absorber”, “flat-plate collector” and “evacuated collector”.

Fig 3.3.2 Unglazed solar absorber

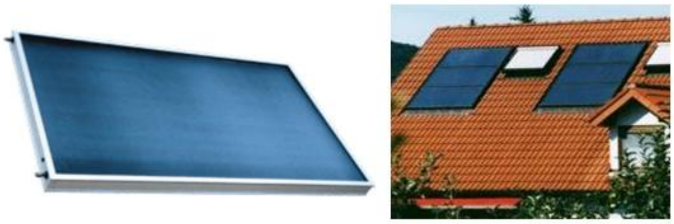


Fig 3.3.3 Flat-plate collector

Fig 3.3.4 Evacuated collector

(Picture source : Institut für Gebäude- und Solartechnik, TU Braunschweig)

“Unglazed solar absorber” is suitable for “Low-temperature solar thermal system”, while “flat-plate collector” and “evacuated tubes” are better in “Medium-temperature” and “High-temperature solar thermal system”. Efficiency of solar collector decreases while system temperature increases.

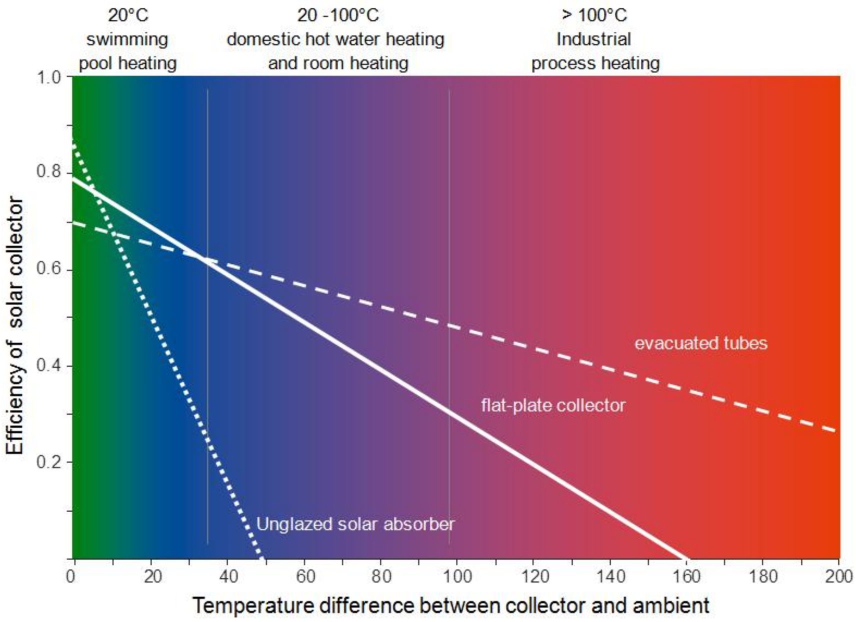


Fig 3.3.5 Efficiency of different solar collector types

(Picture source : Institut für Gebäude- und Solartechnik, TU Braunschweig)

Heat storage is also an important component in solar thermal system. Based on different concepts, there are “short-term heat storage” and “long-term heat storage”. In “short-term heat storage”, solar heat is saved for several hours or days. In “long-term heat storage”, solar heat will be kept in storage for several months. It is possible to capture solar energy in hot summer and use it in cold winter by utilizing “long-term heat storage”.

Fig 3.3.6 Long-term heat storage in Hanover-Kronsberg

(Picture source: M.Norbert Fisch, Thomas Wilken, Christina Stähr. Energie PLUS)

In the context of solar thermal system, “solar fraction (f_{sol})” is an important index. It is the percentage of energy demand that is covered by solar thermal system. [15] It could be calculated as following equation.

$$f_{sol} = \frac{Q_h - Q_{AUX}}{Q_h}$$

Q_h = heating demand [kWh/ (m^2a)]
Q_{AUX} = auxiliary energy [kWh/ (m^2a)]
f_{sol} = solar fraction [%]

3.3.2. Heat pump technology

A heat pump could transfer heat energy from a heat source to a heat sink. There are four main components, which are condenser, expansion valve, evaporator and compressor.

The working fluid circulates through the system. It is pressurized into hot and highly pressurized vapor by compressor. The hot and highly pressurized vapor will be changed into a moderate and highly pressurized liquid and releases heat in condenser. After that, the moderate and highly pressurized liquid will pass the expansion valve and releases its pressure. Then, low pressure liquid enters evaporator, in which the fluid absorbs heat and changes back into vapor. This vapor will return to the compressor and this cycle repeats.

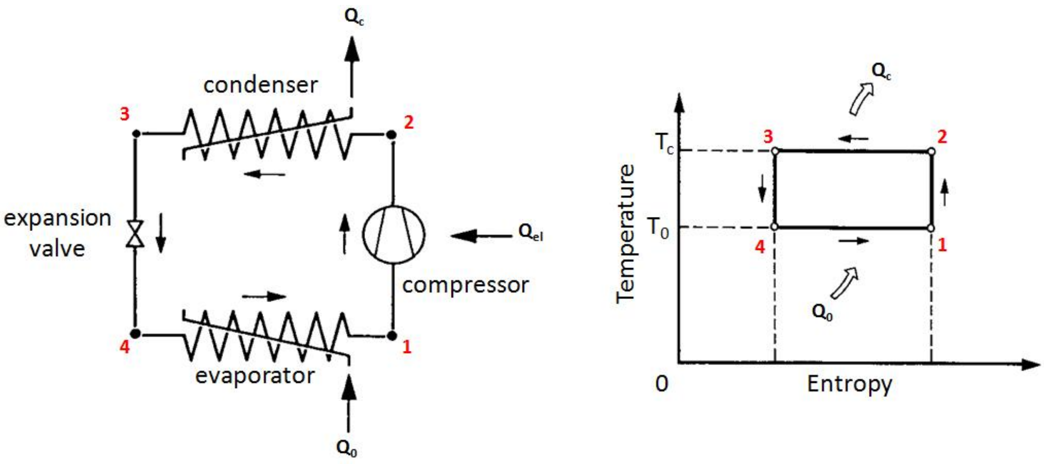


Fig 3.3.7 Principle of heat pump

(Picture source: Institut für Gebäude- und Solartechnik, TU Braunschweig)

Coefficient of Performance (CoP) is the most important index of heat pump. It is defined as the ratio of heat delivered by the heat pump and the electricity supplied to the compressor. The temperature difference between hot side and cold side has big effect on CoP. The value of CoP decreases while temperature difference increases.

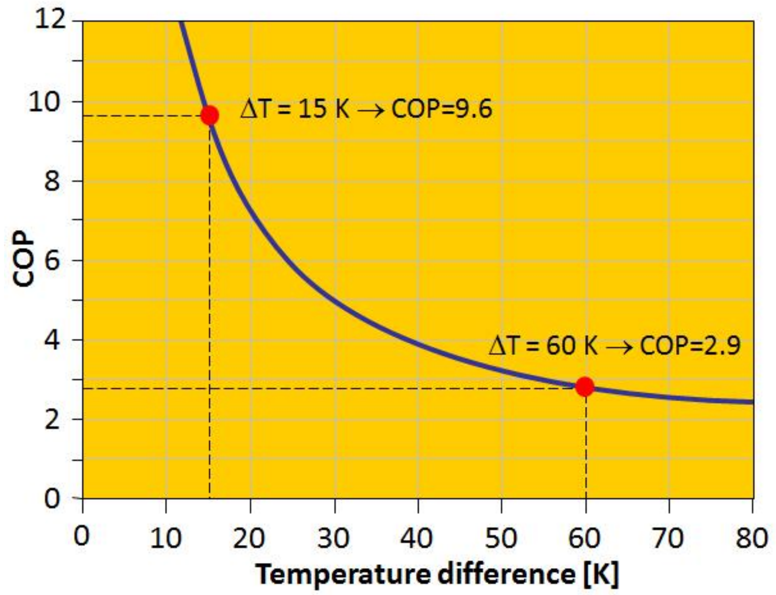


Fig 3.3.8 CoP of heat pump as function of temperature difference (heat sink to heat-source)

(Picture source: Institut für Gebäude- und Solartechnik, TU Braunschweig)

The Seasonal Performance Factor (SPF) is the average value of CoP (Coefficient of Performance) over heating/cooling season. It is the ratio of heat output (in kWh) over the electrical input (in kWh) during whole season, while CoP is the ratio of heat output power (in kW) over the electrical input power (in kW).

$$CoP = \frac{\text{power of heat output [kW]}}{\text{power of electrical input [kW]}}$$

$$SPF = \frac{\text{heat output [kWh]}}{\text{electrical input [kWh]}}$$

Heat pump system could be used both in heating and cooling system. In heating condition, heat pump transfers heat from environment into room. In cooling condition, room heat is removed into environment. Outdoor air, ground soil and ground water are possible to be used as heat source (heating condition) or heat sink (cooling condition).

Air-source heat pump system takes outdoor air as heat source. Air-conditioner is developed on this principle. It is a popular way to supply space cooling. It could also supply space heating in winter as a reversible air-conditioner. However, outdoor air temperature in winter is very low. Coefficient of Performance (CoP) will be strongly reduced because of the big temperature difference between heat source and heat sink (Fig 3.3.8 and Fig 3.3.9).

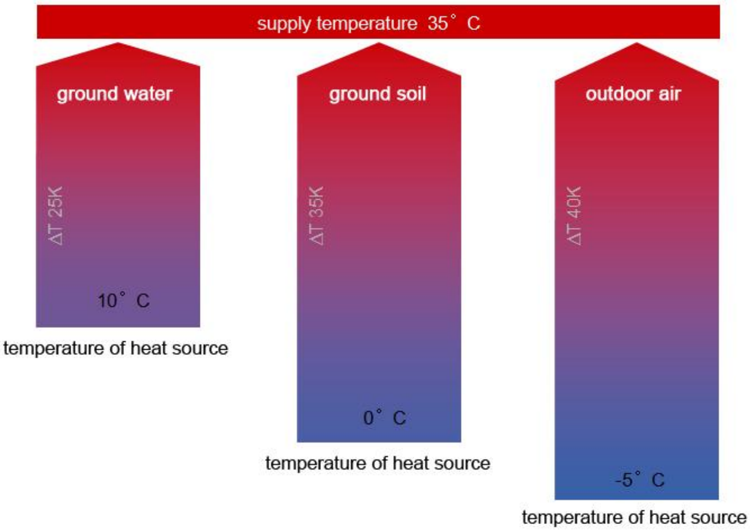


Fig 3.3.9 Temperature difference between heat source and heat supply (winter)

(Picture source: Institut für Gebäude- und Solartechnik, TU Braunschweig)

The temperature fluctuation of ground soil and ground water is less than the air. Compared with air, they are more suitable as heat source. In this thesis, ground-coupled heat pump (GCHP) system is discussed as advanced building service system. GCHP system consists of 4 main components, which are ground-heat-exchanger (GHE), heat pump, heat storage and control equipment. Radiant floor is suitable to work with GCHP for space heating/cooling because of its narrow temperature difference (about 10 K) between supply and return.

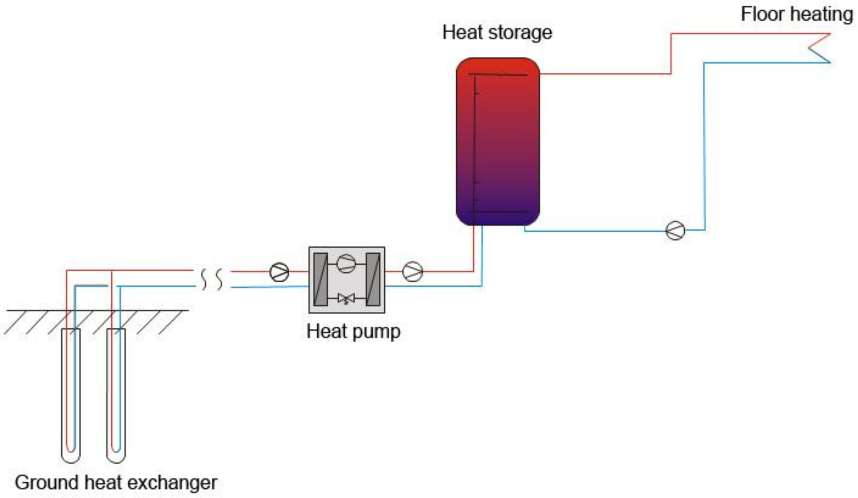


Fig 3.3.10 Ground-coupled heat pump (GCHP) system

With the help of ground-heat-exchanger, free cooling is also possible. Working fluid (e.g. water) circulates directly from ground-heat-exchanger into floor coils and bypassing the heat pump. It is an economical method to achieve living comfort without huge energy consumption. Additionally, this mode of operation could help the thermal regeneration of the soil around ground-heat-exchanger. [3]

3.3.3. Photovoltaic technology

Photovoltaic technology is a method to convert solar energy directly into electricity. This energy conversion takes place in the solar cell. PV module is a packaged, connected assembly of solar cells. It could be integrated with building components, such as roof, wall and window. The usual classification of PV module is according to cell type: monocrystalline silicon (m-Si), polycrystalline silicon (p-Si), amorphous silicon (a-Si) and compound semiconductor such as copper indium selenide (CIS). Among these types, monocrystalline silicon (m-Si) has the highest efficiency. In order to achieve the same power, the space needed for amorphous silicon cells is twice as that for crystalline silicon cells (Fig 3.3.11). [3]

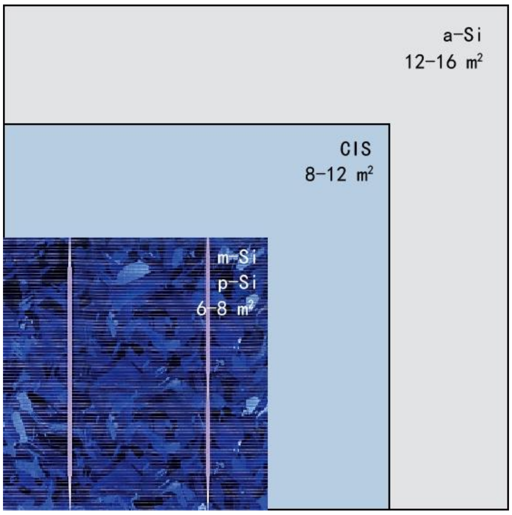


Fig 3.3.11 Required PV-module area for 1 kW_P depending on type of solar cells

(Picture source: M.Norbert Fisch, Thomas Wilken, Christina Stähr. Energie PLUS)

In Germany, with optimal orientation, the amount of solar yield (PV system) is about 800 ~ 1000 kWh/kW_P. The energy amortization time[2] is about three years. [3] Compared with the predicted life span of 25 years for PV system, it is quite short. Because of rich sunshine in China, the amount of solar yield is about 900 ~ 1400 kWh /kW_P. There is big potential of PV technology for Chinese buildings in the future.

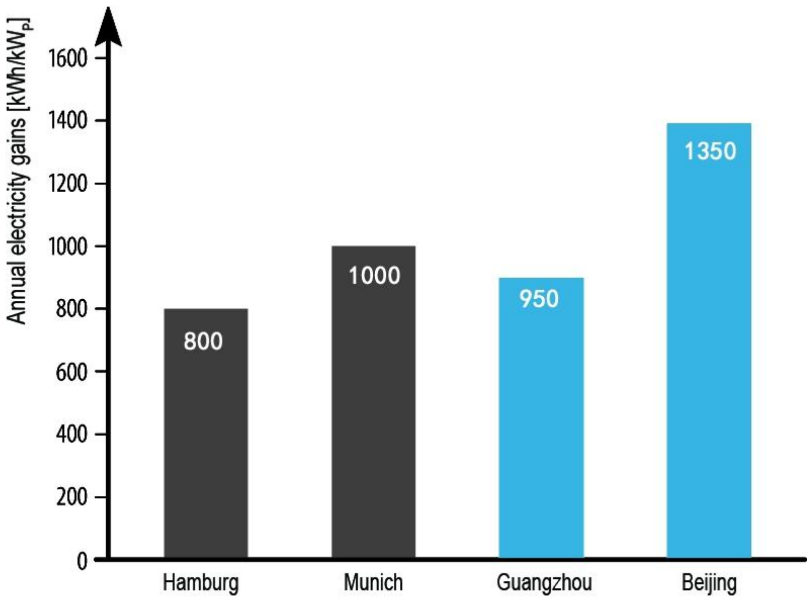


Fig 3.3.12 Annual electricity gain of PV system at four cities

PV electricity could be used in building itself or fed into electricity grid. According to different energy concepts, there are two types of PV system, which are "Island system" and "Grid-connected system".

[2] The energy amortization time refers to the time required for PV plant to produce the amount of energy used in their manufacture.

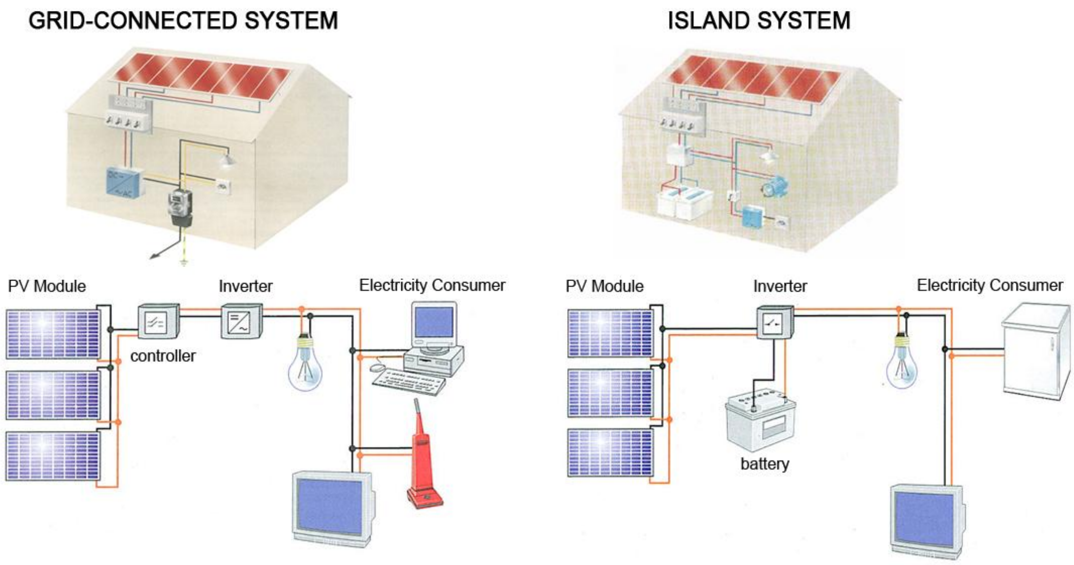


Fig 3.3.13 "Grid-connected system" and "island system"

(Picture source: Institut für Gebäude- und Solartechnik, TU Braunschweig)

In "Island system", there is no connection with public grid. Backup battery is necessary to save electricity surplus for later use. In "Grid-connected system", electricity could be drawn from public grid when PV electricity is not enough. In a sunny day, excess PV electricity will be fed into electricity grid. It is more flexible but complicated. Both of these PV systems change the building into a small power station. Building-integrated PV system is the most important step on the way to "Energy Plus".

Chapter 4

RESULTS

AND DISCUSSION

4.1. Building Envelope

4.1.1. Thermal Insulation of External Wall

Heat transmission losses of external wall could be reduced by increasing the thickness of thermal insulation and reducing the thermal conductivity. However, thicker insulation leads to higher investment. There should be an optimal thickness, which could make the balance between increased investment for thermal insulation and the decreased cost for heating and cooling.

4.1.1.1. Optimal thermal insulation

Heat transmission of external wall

a) Heating period

In the heating period, heat transmission losses of opaque external wall could be described as equation (1).

$$Q_{th-wall} = A_{wall} \times U_{\text{wall}} \times \Delta T_h \times t_h = A_{wall} \times U_{\text{wall}} \times HDD_{18} \times 0.024 \qquad \text{[kWh/a]} \qquad (1)$$

A_{wall} = the area of insulated wall [m^2]

HDD_{18} = heating degree-days [K•d/a] , (24 is used to change unit from [K•d/a] to [K•h/a])

U_{wall} = heat transfer coefficient of external wall [W/ (m^{2}K)]

(0.01 is used to change unit from [W/ (m^{2}K)] to [kW/ (m^{2}K)])

t_h = heating duration [h]

ΔT_h = temperature difference between indoor and outdoor air in heating period [K]

(Indoor temperature is supposed to be 18 ℃ in heating period.)

In the service life (N years) of insulation material, heat transmission losses of opaque external wall is calculated by equation (2).

$$\begin{aligned} N \times Q_{th-wall} &= N \times A_{wall} \times U_{\text{wall}} \times HDD_{18} \times 0.024 \\ &= N \times A_{wall} \times \frac{1}{R_{wo} + \delta_M / \lambda_M} \times HDD_{18} \times 0.024 \qquad \text{[kWh]} \qquad (2) \\ &= \frac{N \times A_{wall} \times \lambda_M \times HDD_{18} \times 0.024}{R_{wo} \times \lambda_M + \delta_M} \end{aligned}$$

λ_M = heat conductivity of insulation material [W/ (m•K)]

δ_M = thickness of thermal insulation [m]

R_{wo} = total thermal resistance of external wall (including inner and external surface resistance R_w, R_i) except thermal insulation [(m^{2}K)/W]

N = service life of thermal insulation [a]

b) Cooling period

Heat transmission gains of external wall in cooling period could be described as following equation (3). The total heat-gain in service life (N years) could be calculated as equation (4).

$$Q_{tc-wall} = A_{wall} \times U_{\mathrm{wall}} \times \Delta T_c \times t_c = A_{wall} \times U_{\mathrm{wall}} \times CDD_{26} \times 0.024 \qquad \text{[kWh/a]} \qquad (3)$$

CDD_{26} = cooling degree-days [K•d/a]

t_c = cooling duration [h]

ΔT_c = temperature difference between indoor and outdoor air in cooling period [K]

(Indoor temperature is supposed to be 26 ℃ in cooling period.)

$$\begin{aligned} N \times Q_{tc-wall} &= N \times A_{wall} \times U_{\mathrm{wall}} \times CDD_{26} \times 0.024 \\ &= N \times A_{wall} \times \frac{1}{R_{wo} + \delta_M / \lambda_M} \times CDD_{26} \times 0.024 \qquad \text{[kWh]} \qquad (4) \\ &= \frac{N \times A_{wall} \times \lambda_M \times CDD_{26} \times 0.024}{R_{wo} \times \lambda_M + \delta_M} \end{aligned}$$

Energy cost

Heat transmission of opaque external wall has to be covered by space heating and cooling. Energy cost could be shown as equation (5) and (6).

In heating period,

$$C_{th-wall} = \frac{N \times Q_{th-wall}}{\eta_h} \times C_{fh} = N \times A_{wall} \times U_{\mathrm{wall}} \times HDD_{18} \times 0.024 \times \frac{C_{fh}}{\eta_h} \qquad [€] \quad (5)$$

In cooling period,

$$C_{tc-wall} = \frac{N \times Q_{tc-wall}}{\eta_c} \times C_{fc} = N \times A_{wall} \times U_{\mathrm{wall}} \times CDD_{26} \times 0.024 \times \frac{C_{fc}}{\eta_c} \qquad [€] \quad (6)$$

In service life (N years),

$$\begin{aligned} C_{th-wall} + C_{tc-wall} &= \frac{N \times Q_{th-wall} \times C_{fh}}{\eta_h} + \frac{N \times Q_{tc-wall} \times C_{fc}}{\eta_c} \qquad [€] \qquad (7) \\ &= N \times U_{wall} \times A_{wall} \times \left[\frac{0.024 \times HDD_{18} \times C_{fh}}{\eta_h} + \frac{0.024 \times CDD_{26} \times C_{fc}}{\eta_c} \right] \end{aligned}$$

$C_{tc\text{-}wall}$ = energy cost of space cooling to cover heat transmission of opaque external wall [€]

$C_{th\text{-}wall}$ = energy cost of space heating to cover heat transmission of opaque external wall [€]

η_h = efficiency of heating system

η_c = efficiency of cooling system

C_{fh} = heating fuel price [€/kWh]

C_{fc} = cooling fuel price [€/kWh]
N = service life of thermal insulation [a]

Since climate condition, fuel price and building service system are already known, equation (7) could be simplified with constant K (equation 8).

$$C_{th-wall} + C_{tc-wall} = N \times U_{wall} \times A_{wall} \times K = \frac{N \times K \times A_{wall}}{R_{wo} + R_M} = \frac{N \times K \times A_{wall} \times \lambda_M}{R_{wo} \times \lambda_M + \delta_M} \quad [€] \qquad (8)$$

The investment for thermal insulation could be calculated by equation (9).

$$C_{insulation} = C_M \times A_{wall} \times \delta_M + C_L \quad [€] \qquad (9)$$

$C_{insulation}$ = cost of thermal insulation [€]
C_L = labor cost [€]
C_M = price of insulation material [€/m^3]
δ_M = thickness of insulation material [m]

Based on equation (8) and (9), the total cost is shown as equation (10).

$$C_{th-wall} + C_{tc-wall} + C_{insulation} = \frac{N \times K \times A_{wall} \times \lambda_M}{R_{wo} \times \lambda_M + \delta_M} + C_M \times A_{wall} \times \delta_M + C_L \quad [€] \qquad (10)$$

If
$$\begin{aligned} y &= C_{th-wall} + C_{tc-wall} + C_{insulation} \\ x &= \delta_M \\ a &= N \times K \times A_{wall} \times \lambda_M \\ b &= R_{wo} \times \lambda_M \\ c &= C_M \times A_{wall} \\ d &= C_L \end{aligned}$$
, equation (10) could be shown as $y = \frac{a}{b+x} + cx + d$.

$$\Rightarrow \frac{\delta y}{\delta x} = \left(\frac{a}{b+x} + cx + d \right)'$$

$$= \left(\frac{a}{b+x} \right)' + (cx)' + (d)'$$

$$= a \times \left(\frac{1}{b+x} \right)' + c$$

$$= a \times (-1) \times (b+x)^{-2} + c$$

When $\frac{\delta y}{\delta x} = 0$, $y = \frac{a}{b+x} + cx + d$ achieves the lowest value.

$$\frac{dy}{dx} = a \times (-1) \times (b + x)^{-2} + c = 0$$
$$\Rightarrow a \times (b + x)^{-2} = c$$
$$\Rightarrow c \times (b + x)^{2} = a$$
$$\Rightarrow cx^{2} + 2bcx + (b^{2}c - a) = 0$$
$$\Rightarrow x = \sqrt{\frac{a}{c}} - b$$

$$\delta_M = \sqrt{\frac{N \times K \times \lambda_M}{C_M}} - R_{wo} \times \lambda_M$$

When the total cost (equation 10) achieves the lowest value, the thickness (δ_M) is the optimal thickness of thermal insulation (equation 11).

$$\delta_M = \sqrt{\frac{N \times K \times \lambda_M}{C_M}} - R_{wo} \times \lambda_M$$

$$K = \frac{\alpha \times C_{fh}}{\eta_h} + \frac{\beta \times C_{fc}}{\eta_c} \tag{11}$$
$$\alpha = 0.024 \times HDD_{18}$$
$$\beta = 0.024 \times CDD_{26}$$

Optimal thickness of thermal insulation in different climate zones

According to equation (11), climate condition (α and β), the characteristic of heating and cooling system (C_f and ŋ), and the type of insulation material (C_M and λ_M) are three important factors. Based on heating degree days and cooling degree days, α and β in each city are calculated and shown in Table 4.1.1. Details about building service systems are shown as Table 4.1.2 and Table 4.1.3.

	URUMQI	BEIJING	SHANGHAI	GUANGZHOU	KUNMING
HDD_{18} [K•d/a]	4390	2750	1711	397	1213
CDD_{26} [K•d/a]	18	60	178	310	0
$\alpha=0.024\times HDD_{18}$	105.4	66.0	41.1	9.5	29.1
$\beta=0.024\times CDD_{26}$	0.4	1.4	4.3	7.4	0.0

Table 4.1.1 Heating and cooling degree days in each city

Heating System	efficiency of heating system (η_h)	Energy source	Fuel Price (C_{fh})
Coal-Fired Boiler	0.7	coal	0.01 €/kWh
Gas-Fired Boiler	0.9	gas	0.03 €/kWh
Reversible air-conditioner	1.9	electricity	0.08 €/kWh

Table 4.1.2 Building heating system in each city

Cooling System	efficiency of cooling system (η_c)	Energy source	Fuel Price (C_{fc})
Air-Conditioner	2.3	electricity	0.08 €/kWh

Table 4.1.3 Building cooling system in each city

Optimal thicknesses of different thermal insulation vary according to heat conductivity and material price. In Chinese residential buildings, expanded polystyrene (EPS), extruded polystyrene (XPS) are most popular insulation materials. Details are listed as Table 4.1.4.

Material	Heat Conductivity (λ_M)	Price (C_M)
EPS 035	0.035 W/(m•K)	31.25 €/m^3
XPS 040	0.040 W/(m•K)	62.50 €/m^3

Table 4.1.4 Thermal insulation materials

Fig 4.1.1 shows calculation results in each city. The optimal value is much bigger than that in existing buildings (Chapter 4.1.1.2). Service life of thermal insulation is supposed to be 30 years. Thermal resistance of the external wall without thermal insulation (R_{wo}) is 0.3 (m^2K)/W.

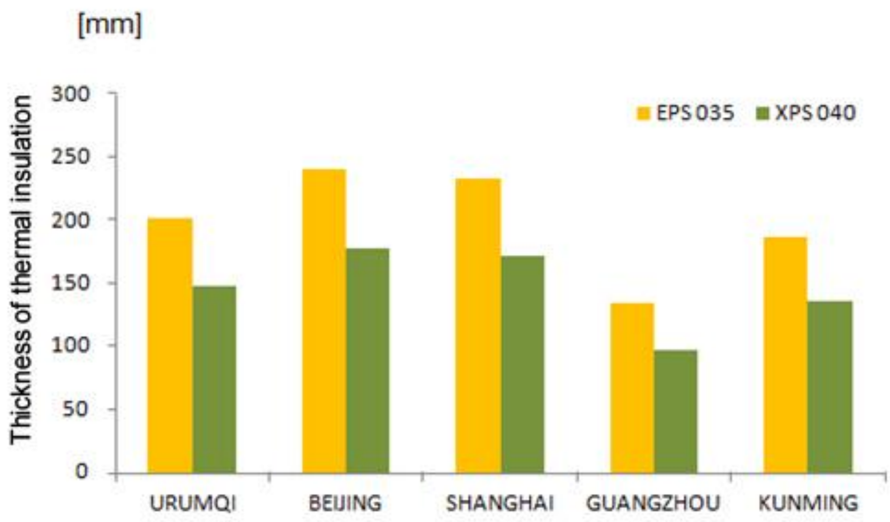


Fig 4.1.1 Optimal thickness of thermal insulation

4.1.1.2. Energy saving potential of thermal insulation

Limited U-value of external wall

U-value (heat transfer coefficient) is a measure of heat loss. Higher U-value means more thermal losses through building envelope. Table 4.1.5 shows the limited U-value of external wall according to Chinese standards. Optimal values are shown at the same time as reference.

	U-wall (standard)	EPS 035 (standard)	U-wall (optimal)	EPS 035 (optimal)
	W/ (m^2K)	mm	W/ (m^2K)	mm
Urumqi	0.45	67	0.22	202
Beijing	0.55	53	0.18	241
Shanghai	0.80	33	0.19	233
Guangzhou	0.70	40	0.33	134
Kunming	1.50	13	0.24	186

Table 4.1.5 U-value of external wall

Increasing the thickness of EPS

As shown in Table 4.1.5, the optimal thickness of EPS in each city is always thicker than the required thickness in energy saving standards. When it is increased from the required value to the optimal value, the U-value of external wall could be reduced. Energy cost for space heating and cooling will be saved. In service life, saved energy cost is more than extra investment for thermal insulation.

Take the basic model in Shanghai as an example (Chapter 2.2.1). When the thickness of thermal insulation (EPS) increases from 35 mm (standard) to 235 mm (optimal), yearly energy demand of space heating and cooling could be 13% reduced (simulation result). Though the investment for 235 mm EPS is higher than 35mm EPS, the total cost in service life (30 years) is lower.

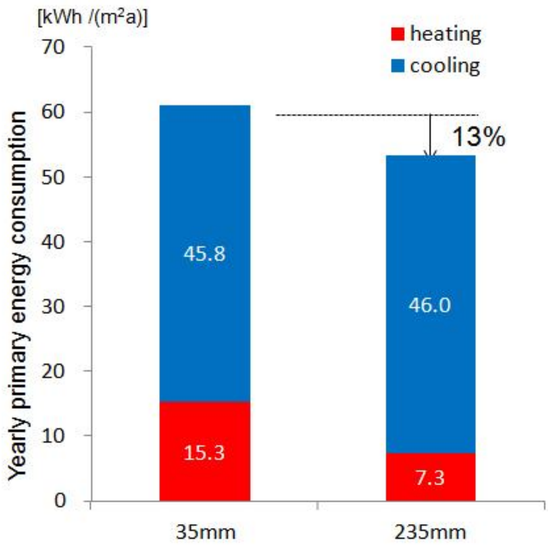


Fig 4.1.2 Heating and cooling demand

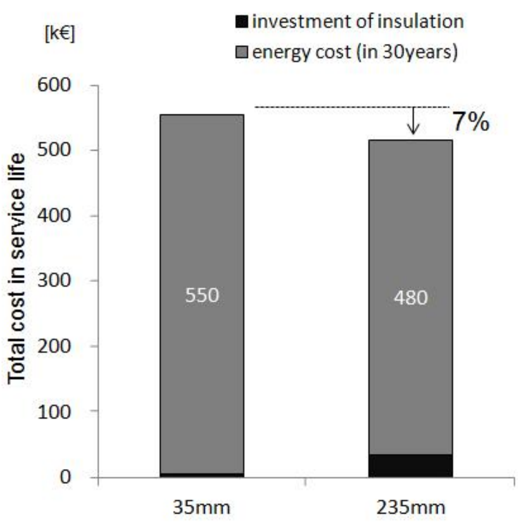


Fig 4.1.3 Total cost in service life (30 years)

4.1.1.3. Conclusion

Thermal performance of building envelope could be improved by reducing U-value of external wall. In this chapter, economical optimal thickness of EPS and XPS are calculated to achieve the lowest cost in service life (30a). Considering current building heating / cooling systems and energy price, the optimal thickness of EPS is between 130~240 mm.

4.1.2. External windows

Compared with external wall, there are more heat transmission losses through windows, because the heat transfer coefficient (U-value) of glazing is higher than that of opaque wall. However, glazing transfers solar gains and sunlight into rooms. This will reduce heating demand of space and artificial lighting. Besides of its contribution in energy balance, window is also an important transparent element of building facade. Architects prefer to big windows in order to get better view of landscape. How can architects make decision for window size? Are large windows good or bad for energy efficient residential buildings in China? Which glazing type is the most suitable in each city? Which type should be avoided? All these questions will be discussed in this Chapter.

4.1.2.1. Energy balance of external windows

There are two parts in energy balance of external windows, which are solar gain (Q_{sg}) and heat transfer ($Q_{t\text{-}window}$).

In heating period

The amount of solar gains ($Q_{sg\text{-}h}$) could be estimated as equation (12).

$$Q_{sg-h} = Q_{sol-h} \times A_{window} \times g \qquad \text{[kWh/a]} \qquad (12)$$

$Q_{sol\text{-}h}$ = solar radiation on window in heating period [kWh/ (m^{2}a)]
A_{window} = window area [m^2]
g = “g-value”, solar heat gain factor

The heat transmission losses through windows could be described as equation (13).

$$Q_{th-window} = A_{window} \times U_{\text{window}} \times \Delta T_h \times t_h = A_{window} \times U_{\text{window}} \times HDD_{18} \times 0.024 \qquad \text{[kWh/a]} \qquad (13)$$

A_{window} = the area of windows [m^2]
HDD_{18} = heating degree-days [K•d/a] (24 is used to change unit from [K•d/a] to [K•h/a])
U_{window} = heat transfer coefficient of glazing [W/ (m^{2}K)]
t_h = heating duration [h]
ΔT_h = temperature difference between indoor and outdoor air in heating period [K]
(0.001 is used to change unit from [W/ (m^{2}K)] to [kW/ (m^{2}K)])

If there is no window (WWR=0), heat transmission losses of opaque wall could be described as equation (14).

$$Q_{th-wall} = A_{wall} \times U_{\text{wall}} \times \Delta T_h \times t_h = A_{wall} \times U_{\text{wall}} \times HDD_{18} \times 0.024 \qquad \text{[kWh/a]} \qquad (14)$$

A_{wall} = the area of insulated wall [m^2]

HDD_{18} = heating degree-days [K•d]   (24 is used to change unit from [K•d] to [K•h])
U_{wall} = heat transfer coefficient of external wall [W/ (m^{2}a)]
t_h = heating duration [h]
ΔT_h = temperature difference between indoor and outdoor air in heating period [K]
(0.001 is used to change unit from [W/ (m^{2}K)] to [kW/ (m^{2}K)])

Compared with 1m^2 opaque wall, there is more heat gain in heating period when there is a window on the wall.

$$\begin{aligned} Q_{h-window} &= Q_{sg-h} - (Q_{th-window} - Q_{th-wall}) \\ &= Q_{sol-h} \times g \times A_{window} - U_{\text{window}} \times HDD_{18} \times 0.024 \times A_{window} + U_{\text{wall}} \times HDD_{18} \times 0.024 \times A_{window} \\ &= \left(Q_{sol-h} \times g - (U_{\text{window}} - U_{\text{wall}}) \times HDD_{18} \times 0.024\right) \times WWR \\ &= \left(Q_{sol-h} \times g - \Delta U \times HDD_{18} \times 0.024\right) \times WWR \end{aligned} \quad \text{[kWh/a]} \quad (15)$$

ΔU = difference of U-value between glazing and opaque wall [W/ (m^{2}a)]

According to equation (15), window heat-gains relate to 3 factors, which are solar heat gain factor (g-value), window-to-wall ratio (WWR) and difference of U-value (△U) between glazing and opaque wall.

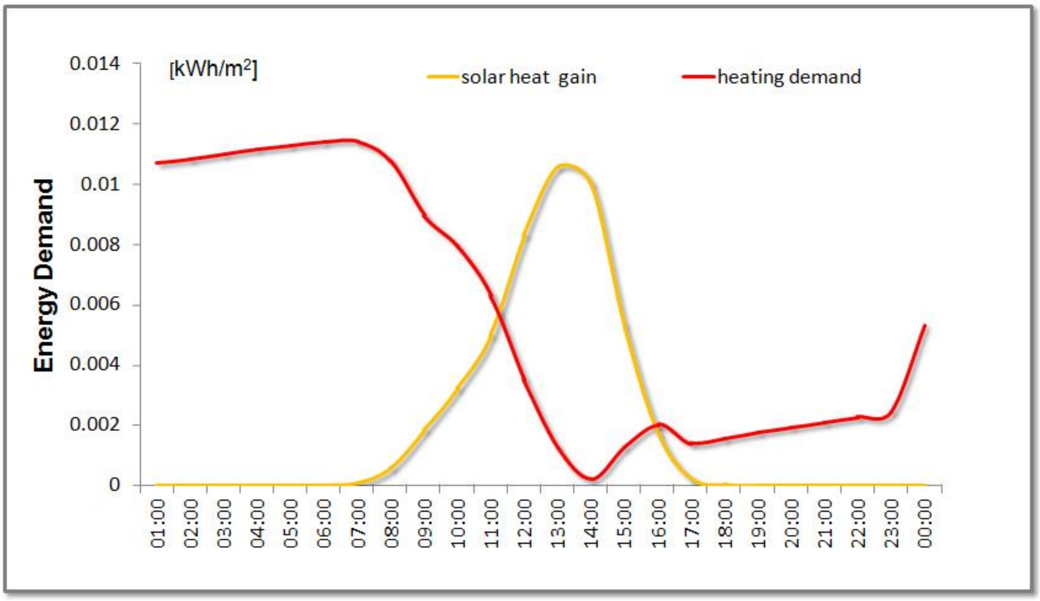


Fig 4.1.4 Energy demand in a winter day (Shanghai)

Since solar heat gain and heating demand are not synchronous (Fig 4.1.4), increased heat gain is not exactly the same as reduced heating demand. The reduced heating demand could be described as equation (16).

$$\eta \times Q_{h-window} = \eta \times \left(Q_{sol-h} \times g - \Delta U \times HDD_{18} \times 0.024\right) \times WWR \quad \text{[kWh/a]} \quad (16)$$

ŋ = solar heat gain effectiveness [-]

In a sunny winter afternoon, solar heat gain is more than heating demand (Fig 4.1.4). Larger window area will transfer more excess solar heat gain, which has to be exhausted by opening windows. Solar heat gain effectiveness will decrease, when window area increases. As shown in Table 4.1.6, solar heat gain effectiveness (ŋ) decreases from 86% to 49%, when WWR increases from 10% to 90%.

window-to-wall ratio (WWR)	solar heat gain [kWh/(m^{2}a)]	heat transfer loss [kWh/(m^{2}a)]	heating demand [kWh/(m^{2}a)]	solar heat gain effectiveness (ŋ)
0	0.0	14.3	22.5	
10%	6.6	16.5	18.6	86%
20%	13.1	19.0	15.7	80%
30%	19.7	22.0	13.6	73%
40%	26.3	25.3	12.2	67%
50%	32.5	28.8	11.2	63%
60%	39.0	32.8	10.5	58%
70%	43.1	36.0	10.5	56%
80%	51.9	41.2	9.6	51%
90%	57.2	45.2	9.6	49%

Table 4.1.6 Solar heat gain effectiveness (ŋ) in heating period (Shanghai, South, Double clear glazing)

Solar heat gain effectiveness (ŋ) varies a little when using different glazing types. Double clear glazing (D-CLE), double Low-E glazing (D-LOE) and double reflect glazing (D-REF) are examined in this thesis. As shown in Fig 4.1.5, double reflect glazing (D-REF) has the smallest reduction of ŋ when WWR increases from 10% to 90%.

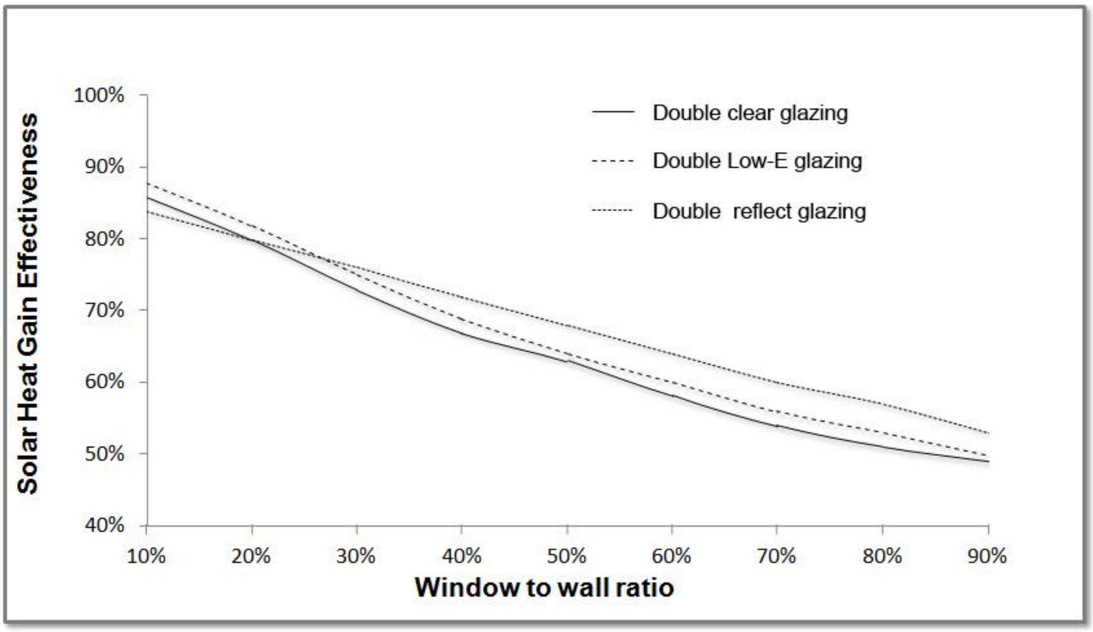


Fig 4.1.5 Different values of solar heat gain effectiveness according to glazing types (Shanghai, South)

In cooling period

Window will transfer excess solar heat gain, which has to be covered by space cooling in summer. Heat transmission through windows will also increase cooling demand. In order to reduce cooling demand, well-designed nature ventilation and shading system are necessary.

4.1.2.2. Window-to-wall ratio (WWR)

The window-to-wall ratio (WWR) is a ratio of window (glazing) area to wall area (Fig 4.1.6). Higher WWR means larger window area on the wall. According to equation (16), WWR plays an important role in energy balance of windows. In this thesis, energy demands for space heating and cooling are simulated with different window-to-wall ratio (10% ~ 90%) in 5 cities.

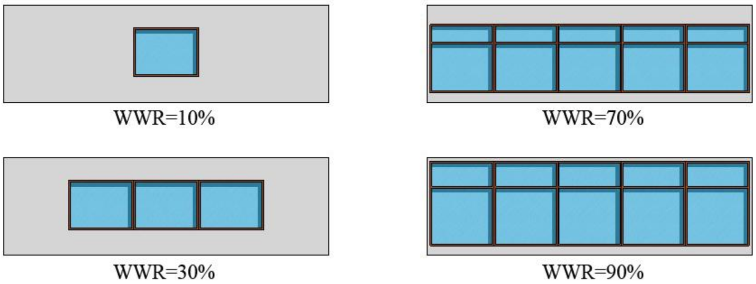


Fig 4.1.6 Window-to-wall ratio (WWR)

As shown in Fig 4.1.7, energy demand for space heating in Urumqi and Beijing decreases when window-to-wall ratio on southern wall increases. Large area of northern windows will loss more heat and increase heating demand. According to that, large southern window (WWR ≧ 50%) and small northern window (WWR < 50%) is suitable in cold cities, such as Urumqi and Beijing.

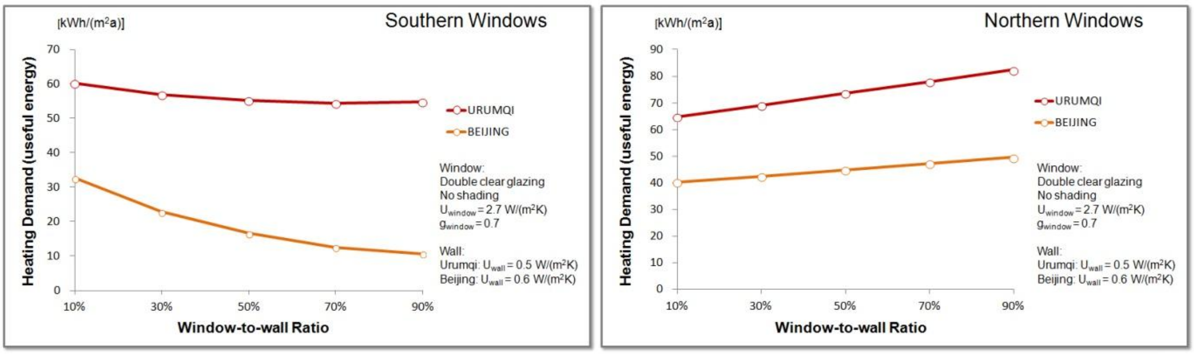


Fig 4.1.7 Yearly heating demand of different window-to-wall ratios for south and north orientation

In cooling period, large window area will transfer more excess solar heat gain and increase energy demand for space cooling (Fig 4.1.8). In warm cities (such as Guangzhou and Kunming), where cooling demand is dominant, small window area (WWR < 50%) is more suitable.

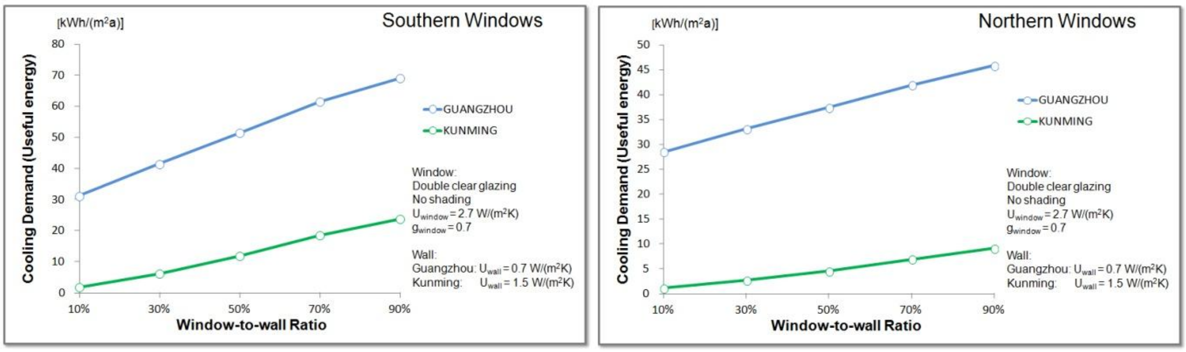


Fig 4.1.8 Yearly cooling demand of different window-to-wall ratios for south and north orientation

In Shanghai, which locates in “hot summer and cold winter zone”, large southern window will reduce heating demand. However, the energy demand for space cooling will be increased at the same time (Fig 4.1.9). Since excess solar heat gain could be reduced by shading system, big southern window with well-designed shading system are suggested in this city.

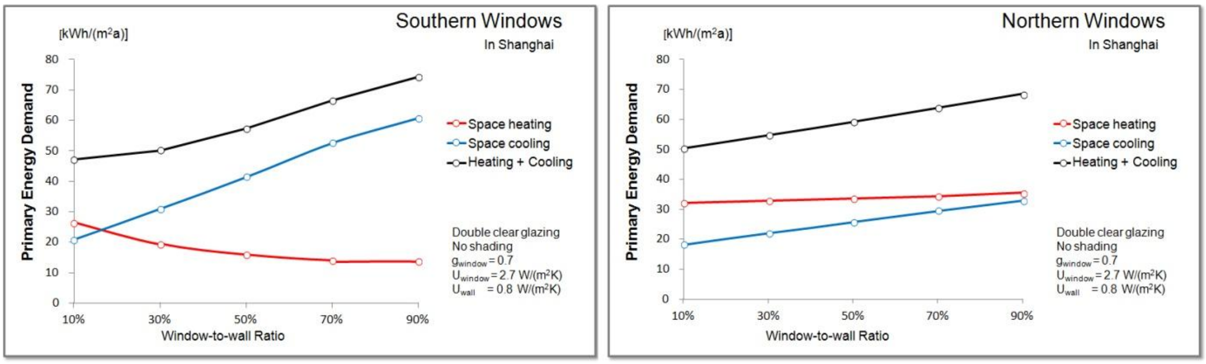


Fig 4.1.9 Yearly energy demand of different window-to-wall ratios for south and north orientation (Shanghai)

4.1.2.3. Glazing types

According to equation (16), g-value and U-value of the glazing have high influence on the energy balance of the building. Three glazing types are discussed in this thesis, which are double clear glazing (D-CLE), double Low-E glazing (D-LOE), and double reflect glazing (D-REF) (Fig 4.1.10). Characteristics of these glazing types are shown as Table 4.1.7.

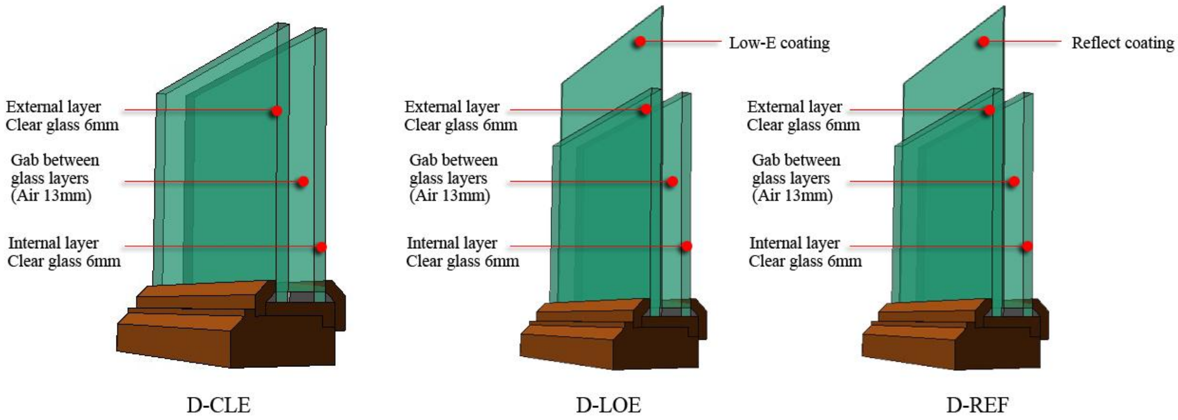


Fig 4.1.10 Construction of different glazing types

Glazing type	g	U_{window} [W/(m^{2}K)]
D-CLE	0.7	2.7
D-LOE	0.6	1.9
D-REF	0.4	2.7

Table 4.1.7 Glazing types

Energy demand of basic model with different glazing types are simulated in each city. In Urumqi and Beijing, where heating demand is dominant, D-LOE could achieve the lowest heating demand (Fig 4.1.11). In Guangzhou and Kunming, where cooling demand is dominant, D-REF is more suitable (Fig 4.1.12).

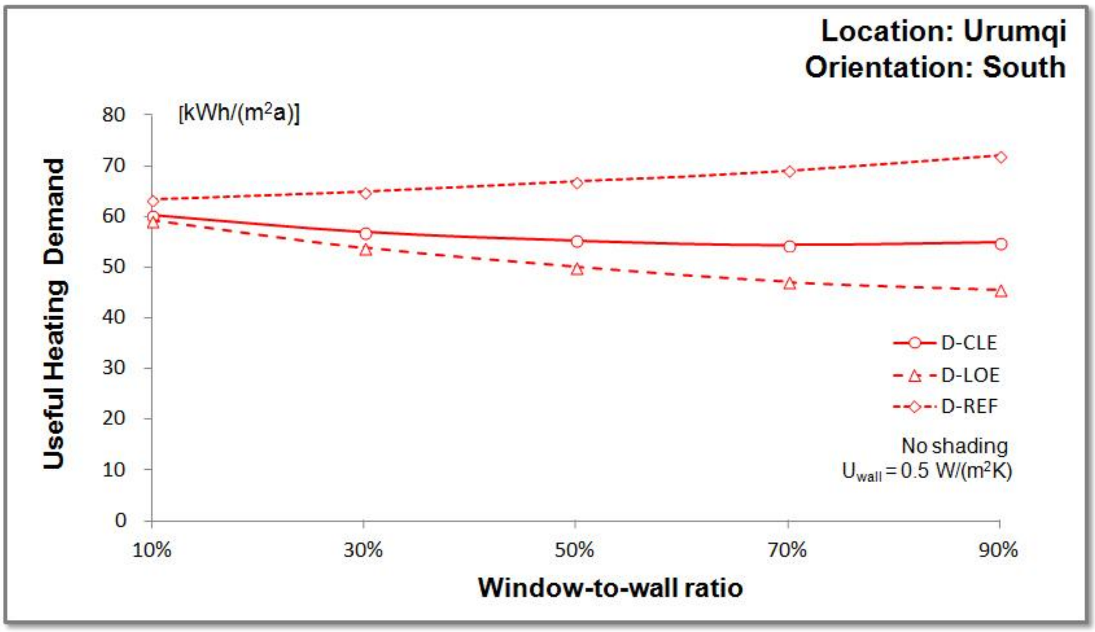


Fig 4.1.11 Heating demand of southern window size in Urumqi

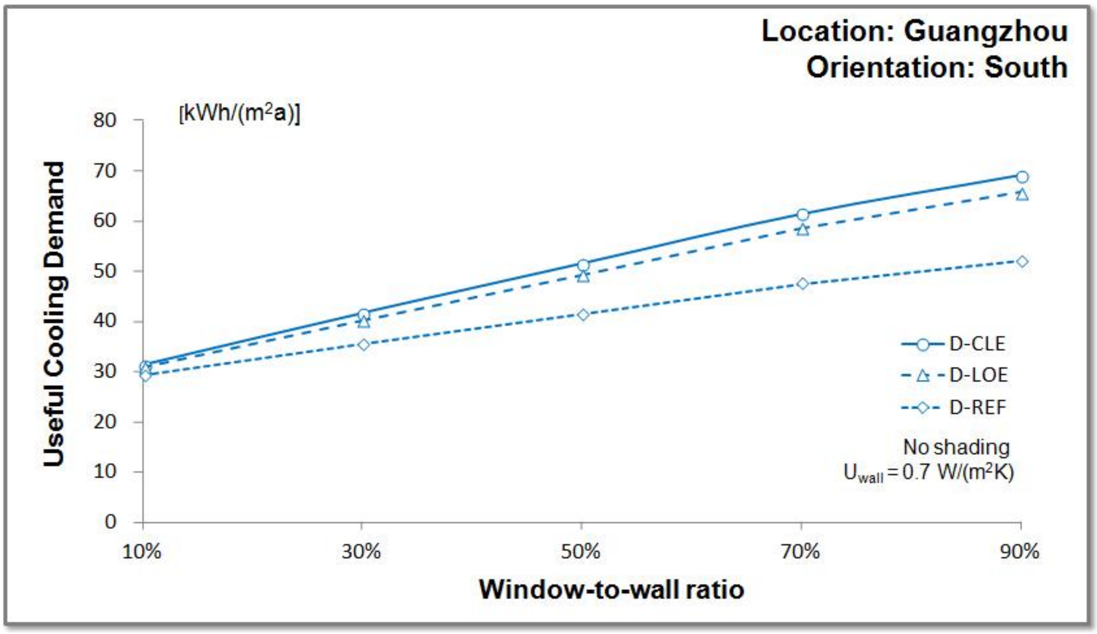


Fig 4.1.12 Cooling demand of southern window size in Guangzhou

In Shanghai, which locates in “Hot summer and cold winter zone”, both heating and cooling demand have to be considered. Fig 4.1.13 shows the relationship between primary energy demand and southern window size in Shanghai. D-LOE is suitable for small windows (WWR<50%), while D-REF is better for big windows (WWR>50%). On northern wall (Fig 4.1.14), D-LOE is always the best choice.

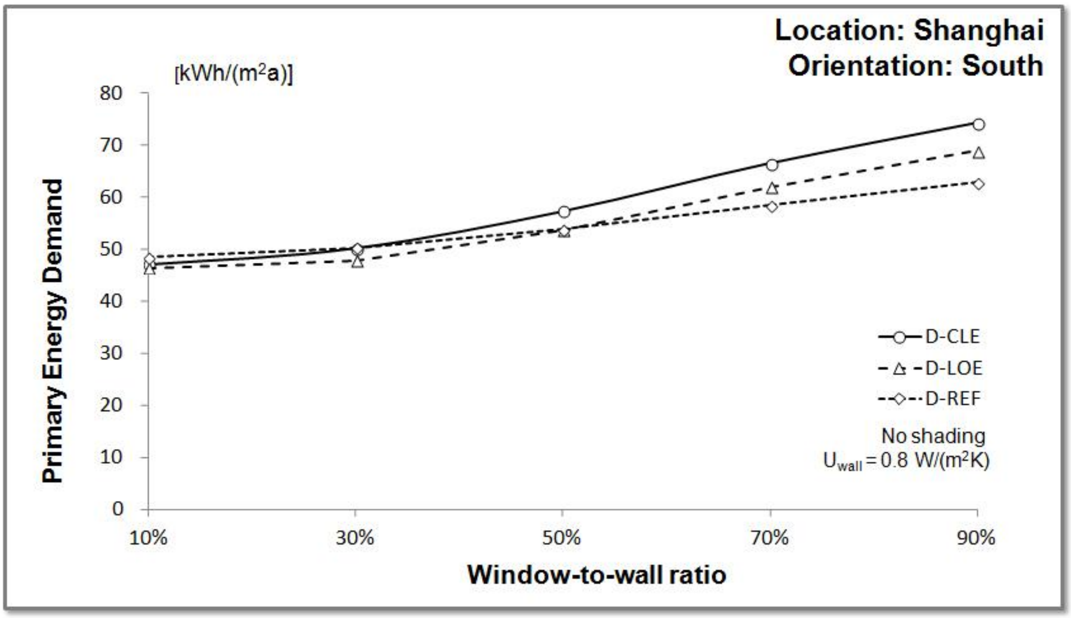


Fig 4.1.13 Primary energy demand of southern window size in Shanghai

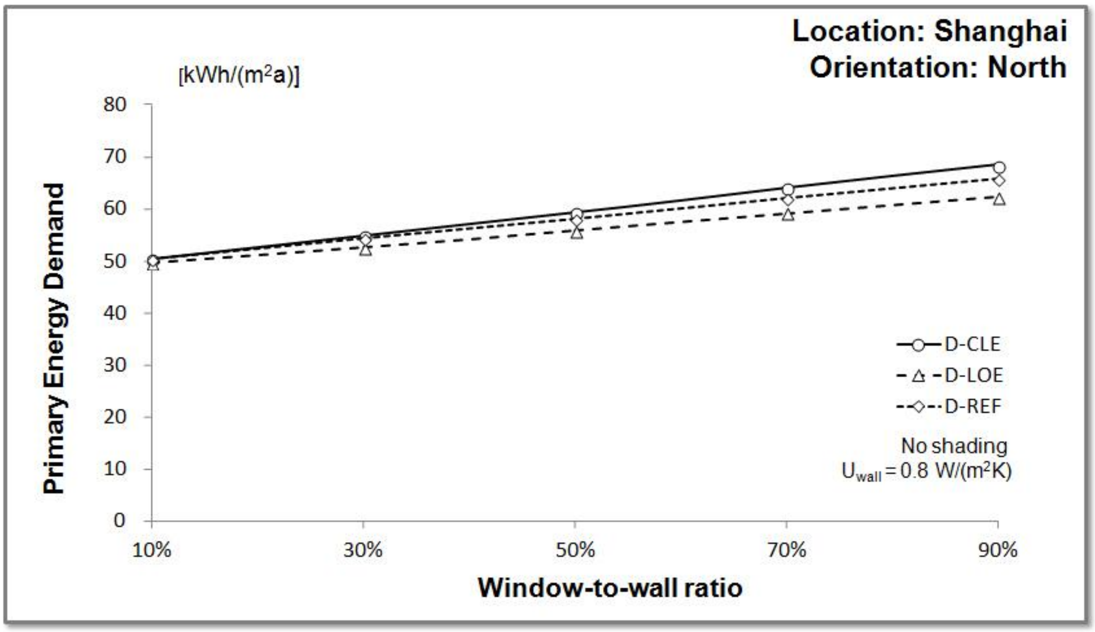


Fig 4.1.14 Primary energy demand of northern window size in Shanghai

4.1.2.4. Conclusion

According to the discussion in Chapter 4.1.2, suggestions about window design in Chinese residential buildings could be concluded as follow.

- ✧ In Urumqi and Beijing, where heating demand is dominant, high window-to-wall ratio (50% ~ 90%) is more suitable for southern windows (common glazing type, g_{window}=0.7, U_{window}=2.7 W/ (m^2K), no shading). Window-to-wall ratio of northern windows should be small. With the consideration of day lighting, window-to-wall ratio of northern windows is suggested to be 20% up to 40%.

- ✧ In Guangzhou and Kunming, where cooling demand is dominant, small window-to-wall ratio (20% up to 40%) is suggested for both northern and southern windows (common glazing type, g_{window}=0.7, U_{window}=2.7 W/ (m^2K), no shading).

- ✧ In Shanghai, window area on southern wall is suggested to be large to reduce heating demand. Shading system should be integrated for southern windows in order to get rid of high cooling demand in summer.

- ✧ Double Low-E glazing (D-LOE) is the most suitable glazing type in Urumqi and Beijing. Double reflect glazing (D-REF) is the best choice in Guangzhou and Kunming.

- ✧ In Shanghai, which locates in “Hot summer and cold winter zone”, Double Low-E glazing (D-LOE) and double reflect glazing (D-REF) are both suitable for southern windows. Double Low-E glazing is better than double reflect glazing when WWR<50%. Double Low-E glazing is also the best choice for northern windows in Shanghai.

4.2. Advanced Building Heating and Cooling Technology

In order to reduce the demand of fossil fuel, advanced building service technologies using renewable energy become popular. Solar thermal system, Ground-coupled heat pump system and Photovoltaic system are the most favorite systems. They are discussed and compared in this Chapter to give recommendations for the building service system in Chinese multi-story residential buildings in the future.

4.2.1. Solar Thermal System

4.2.1.1. Solar energy potential in China

China is one of those countries, which have high solar energy potential. Annual sunshine hours are more than 2000 hours on 2/3 of lands area. In Germany, it is only 1200 ~ 1900 hours. Based on sunshine hours and global solar radiation, China could be divided into 5 solar energy zones.

	Zone Ⅰ	Zone Ⅱ	Zone Ⅲ	Zone Ⅳ	Zone Ⅴ	Germany
sunshine hours [h/a]	2800 ~ 3300	3000 ~ 3200	2200 ~ 3000	1400 ~ 2200	1000 ~ 1400	1200 ~ 1900
global radiation [kWh/(m^{2}a)]	1900 ~ 2300	1600 ~ 1900	1400 ~ 1600	1200 ~ 1400	<1200	900 ~ 1200

Table 4.2.1 Solar energy zones in China

According to the comparison between climate zones and solar energy zones, cities in “severe cold zone”, “cold zone” and “warm zone” mostly belong to zone Ⅰ, Ⅱ and Ⅲ, while cities in “hot summer and cold winter zone” and “hot summer and warm winter zone” belong to zoneⅣ and Ⅴ. There is more solar energy resource in “cold” cities than “hot” cities.

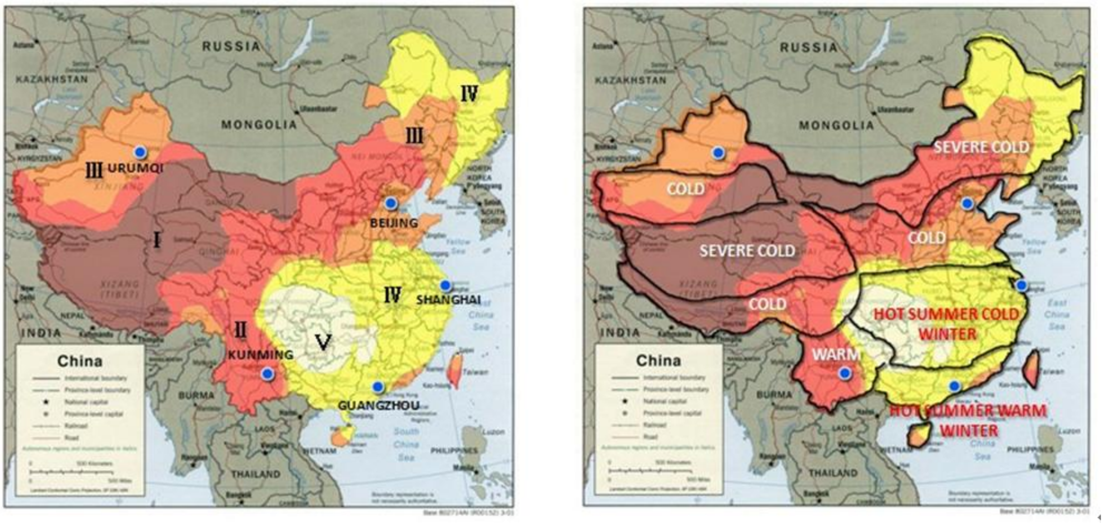


Fig 4.2.1 Solar energy zones and climate zones

4.2.1.2. Tilt angle of solar collector

The tilt angle of solar collecting area (thermal collector, PV modules) has high influence on solar collection. Small tilt angle is more suitable in summer, while big tilt angle is better in winter (Fig 4.2.2). For a whole-year-operating solar thermal system, the tilt angle of solar collector is suggested to be -10° ~ +20° around the latitude of its location in China. [15] Take shanghai (31.2° N, 121.4° E) as an example, the tilt angle of solar collector should be 20° ~ 50° .

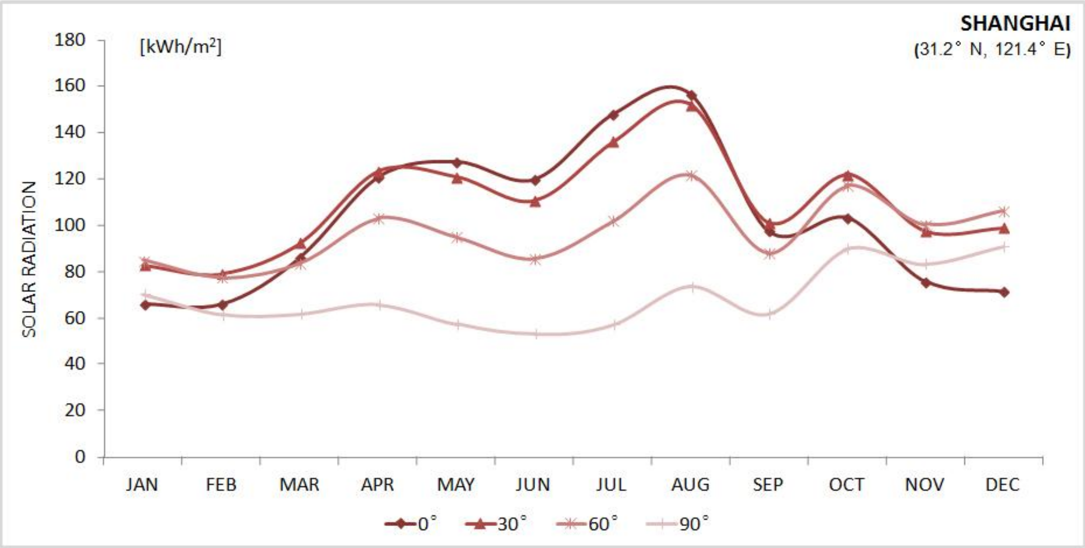


Fig 4.2.2 Monthly solar radiation on tilt surface (orientation: south)

4.2.1.3. Area of solar collector

Principle of solar thermal system is collecting solar energy and changing it into heat. When solar collectors are arranged in rows on flat roof, the distance between rows has to be checked. The minimal distance is calculated according to the latitude of location, tilt angle of collectors (β) and the dimension of collector module. Solar collectors in back row should be kept out of the shadow, which is caused by the front row (Fig 4.2.3).

This calculation could also be done in a small program “Shade calculation Vers4.1” from “Schletter GmbH”. In this program, latitude of location, tilt angle (β) of collectors and the dimension of solar collector are necessary inputs. Minimal distance of rows is shown in graph (Fig 4.2.3) as output. Fig 4.2.4 indicates the dimension of collector module.

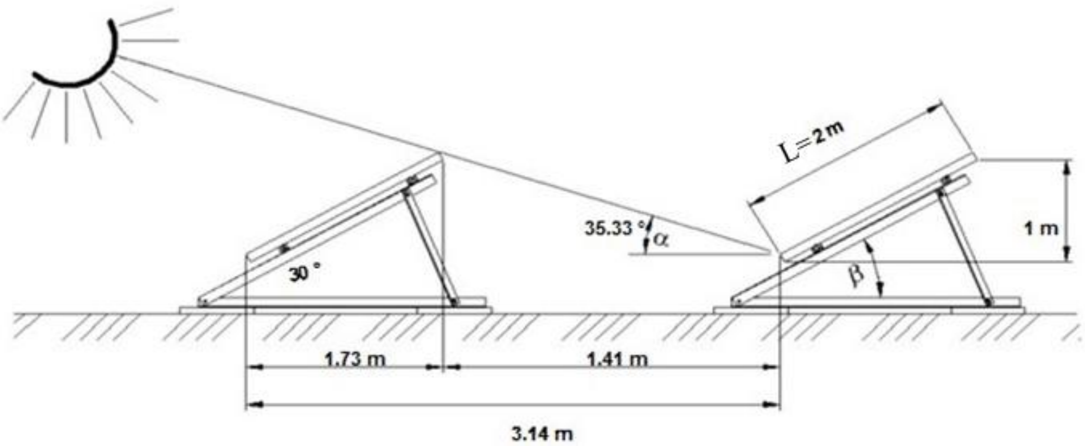


Fig 4.2.3 Example of minimal distance between solar collectors (location: Shanghai, 31.2° N, 121.4° E)

Fig 4.2.4 Dimension of collector module

Based on the minimal distance between rows, the maximal area of solar collectors on flat roof could be calculated. Take the basic model (roof area 600m^2) for example, maximal area of solar collectors is shown as Table 4.2.2. Since latitudes are different, the maximal area of solar collector also varies.

		URUMQI	BEIJING	SHANGHAI	GUANGZHOU	KUNMING
Latitude	°	43.83	39.8	31.17	23.13	25.02
tilt angle	°	45	40	30	25	25
length of collector	m	2	2	2	2	2
distance	m	3.4	2.6	1.4	0.9	1.0
area of collector	m^2	240	360	360	480	480
collector / roof	%	40	60	60	80	80

Table 4.2.2 Area of solar collectors on flat roof (600m^2)

4.2.1.4. System construction and simulation

Solar thermal system, which supplies space heating (SH) and domestic hot water (DHW) for basic model (Chapter 2.2.1), is simulated in the software "Trnsys 16". Small gas boiler works as auxiliary energy. System construction is indicated as Fig 4.2.5.

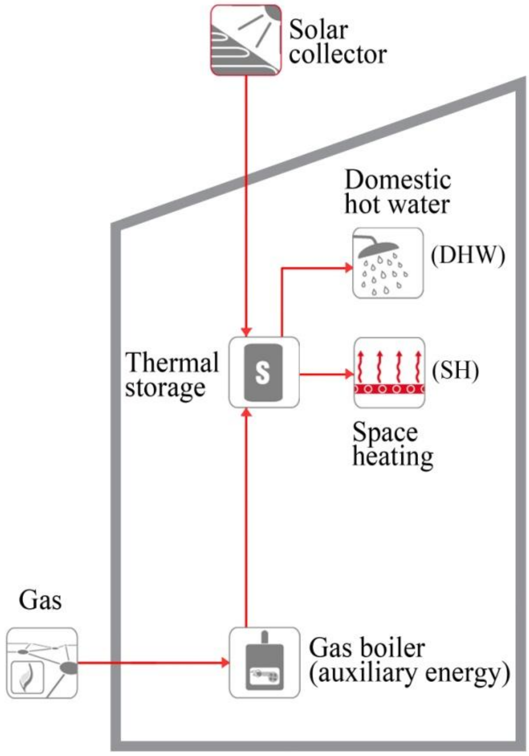


Fig 4.2.5 Solar thermal system (DHW and SH)

Temperature of cold water, which flows into thermal storage from its bottom, is set to be 18 ℃. 35 liter domestic hot water with 60℃ is supplied for each person every day. Simulation condition in a winter day is shown as Fig 4.2.6 and Fig 4.2.7.

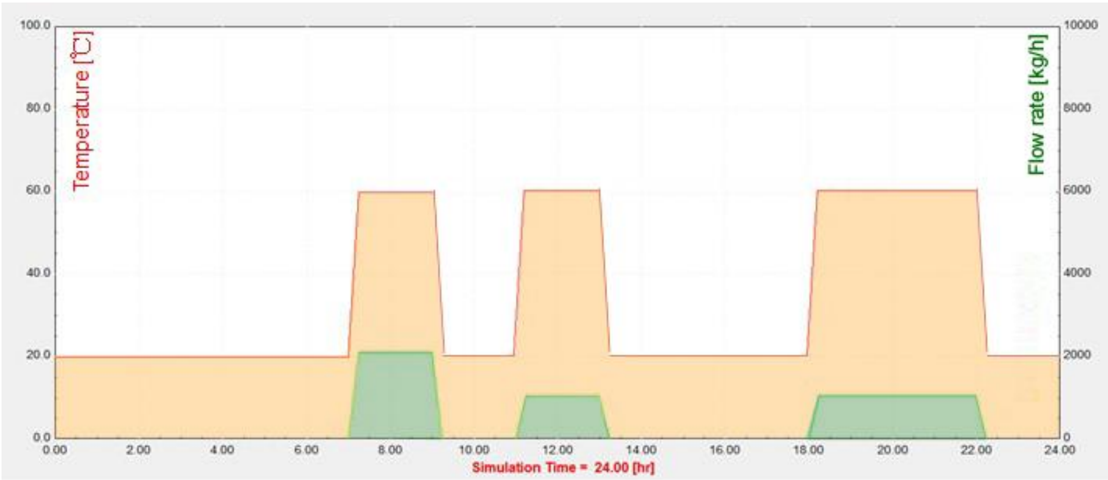


Fig 4.2.6 Simulation condition of domestic hot water

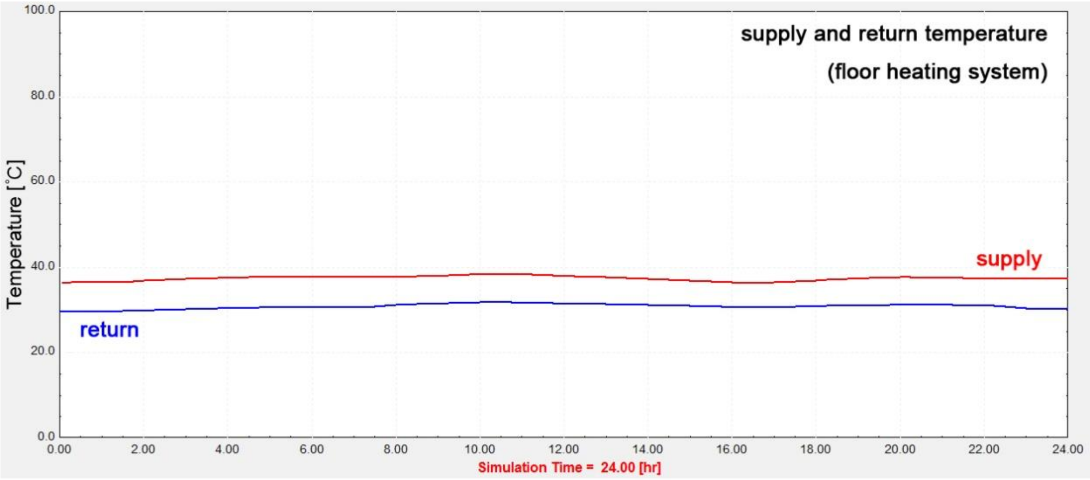


Fig 4.2.7 Simulation condition of solar assisted heating system

Fig 4.2.6 shows the condition of domestic hot water. Green line and red line are "flow rate" and "temperature of domestic hot water", respectively. The temperature of domestic hot water is kept at 60℃, when the flow rate is higher than 0.

Fig 4.2.7 shows the condition of floor heating in a winter day. Supply temperature of floor heating system is variable in order to meet real-time heating demand. Temperature difference between supply and return is kept less than 10 ℃.

Building data are the same as basic model (Chapter 2.2.1). It is an 18-floors residential building. On each floor, there are 6 apartments. Floor area of each apartment is 100m^2. The density of occupancy is 0.03person/m^2.

According to the simulation, more than 20% of monthly heat demand (useful energy for domestic hot water and space heating) could be covered by solar energy in these cities (except Urumqi). In summer, monthly solar fraction could rise to 70%. Solar fraction in Urumqi is lower, because of its huge heating demand (Chapter 2.2.3).

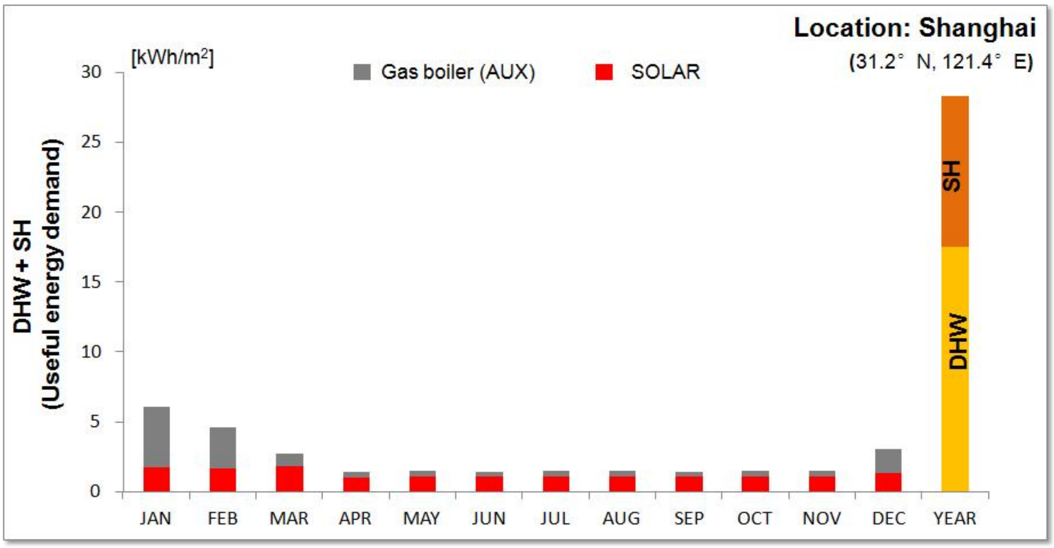


Fig 4.2.8 Energy demand of domestic hot water (DHW) and space heating (SH) in Shanghai

4.2.1.5. Overall building service system

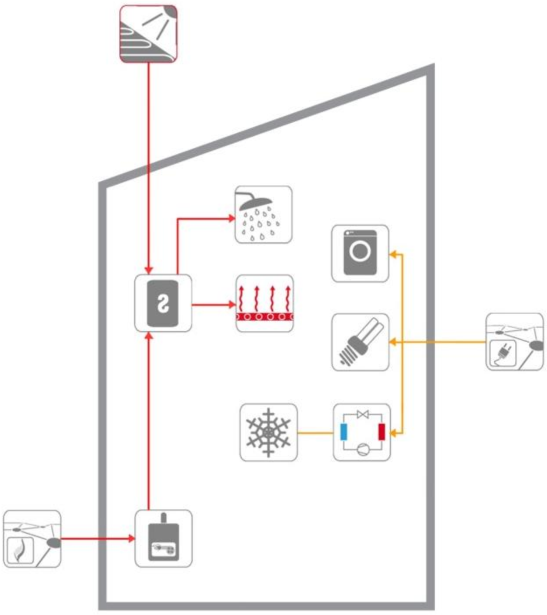


Fig 4.2.9 Building service system-A

In this thesis, overall building service system including space heating, space cooling, domestic hot water, lighting and appliances, is discussed. Four systems (system-A, B, C, D) with different building technologies are examined.

Fig 4.2.9 indicates the design of system-A. Domestic hot water and space heating are supplied by solar thermal system (assisted by gas boiler). Electrical air-conditioner (CoP=2.3) [5] covers cooling demand. According to data in "2011 annual report on China Building Energy efficiency", the electricity demand for lighting and appliance are 5.3 kWh/ (m^2a) and 5.1 kWh/ (m^2a), respectively. [9]

Fig 4.2.10 shows monthly gas and electricity demand of system-A in Shanghai. Building condition is the same as the basic model (Chapter 2.2.1). Yearly gas and electricity demand in other cities is shown as Table 4.2.3. The size of solar thermal system is the same as that described in Chapter 4.2.1.4.

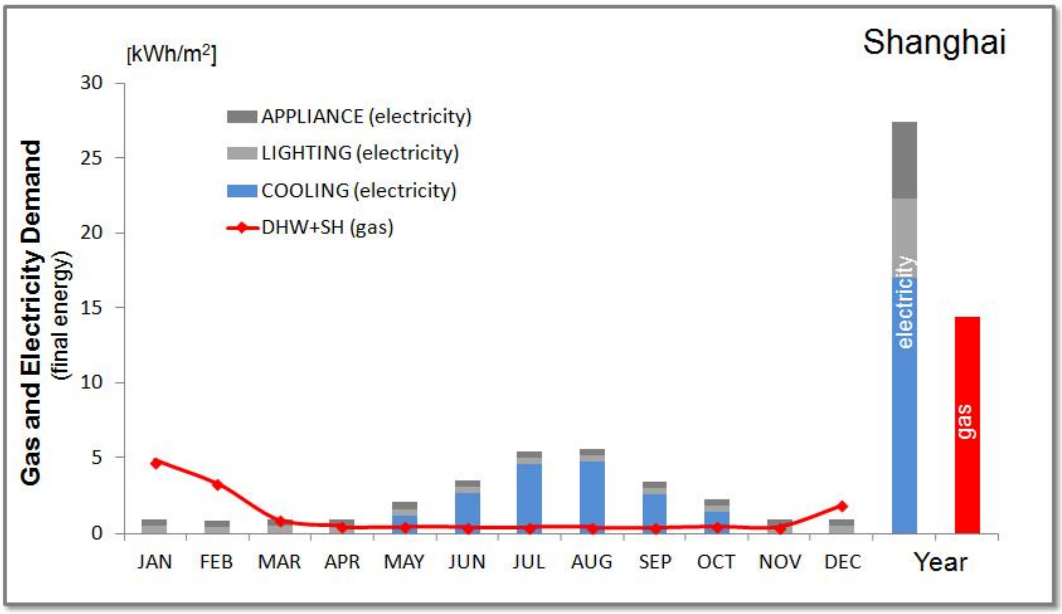


Fig 4.2.10 Gas and electricity demand (final energy) of system-A

Gas and Electricity Demand (final energy) [kWh/(m^{2}a)]		URUMQI	BEIJING	SHANGHAI	GUANGZHOU	KUNMING
DHW+SH	gas	70	23	14	7.2	5.8
COOLING	electricity	14	17	17	24	6.7
LIGHTING	electricity	5.3	5.3	5.3	5.3	5.3
APPLIANCE	electricity	5.1	5.1	5.1	5.1	5.1

Table 4.2.3 Yearly gas and electricity demand (final energy) of system-A

Based on the PE-factor of gas (PE=1.1) and electricity (PE=2.7), yearly primary energy demand could be calculated (Fig 4.2.11 and Fig 4.2.12).

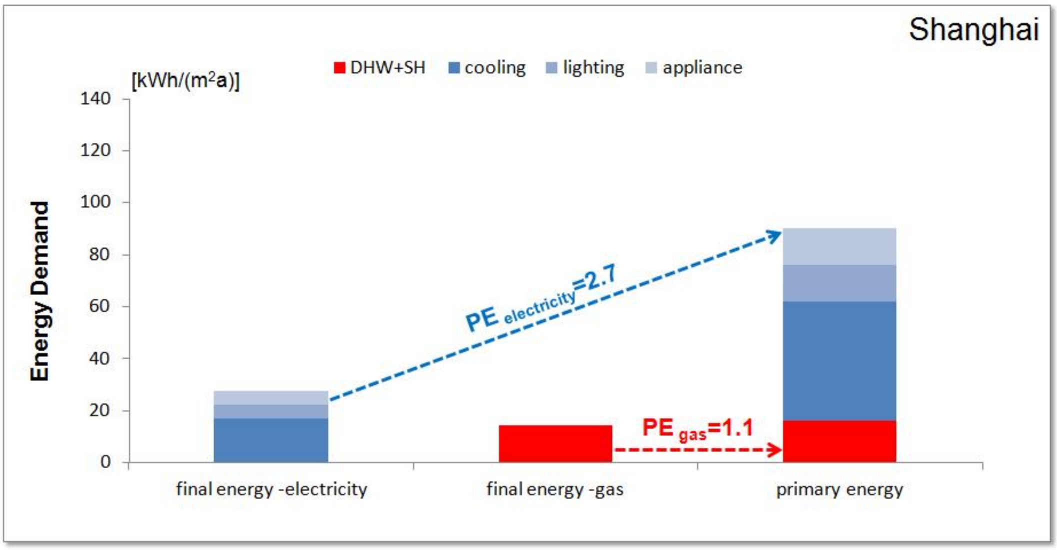


Fig 4.2.11 Yearly primary energy demand in Shanghai (System-A)

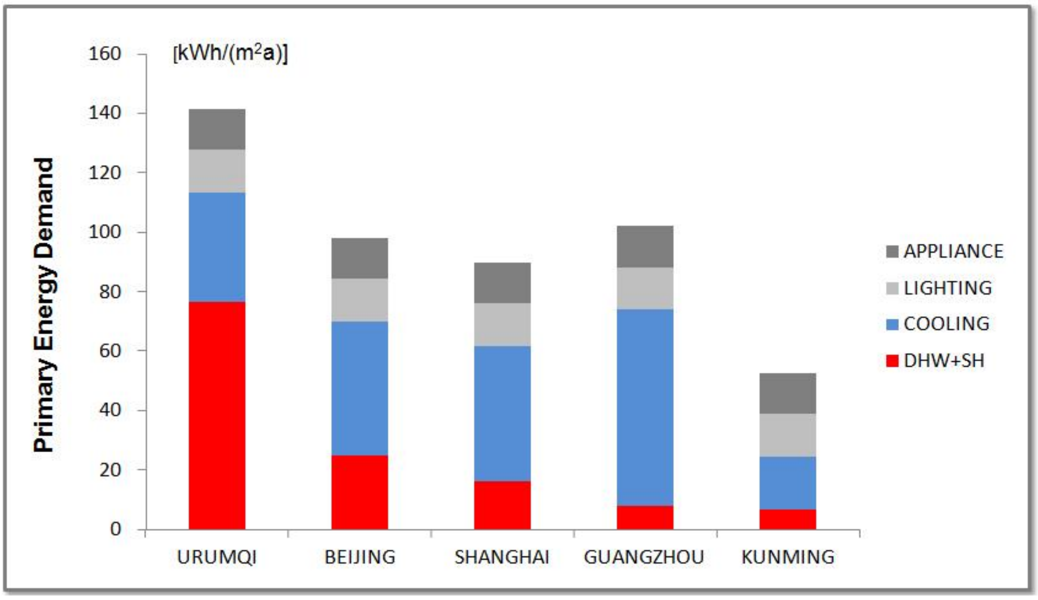


Fig 4.2.12 Primary energy demand of system-A

Compared with reference systems (Chapter 2.2.2.5), system-A could save 13%~25% primary energy in these cities.

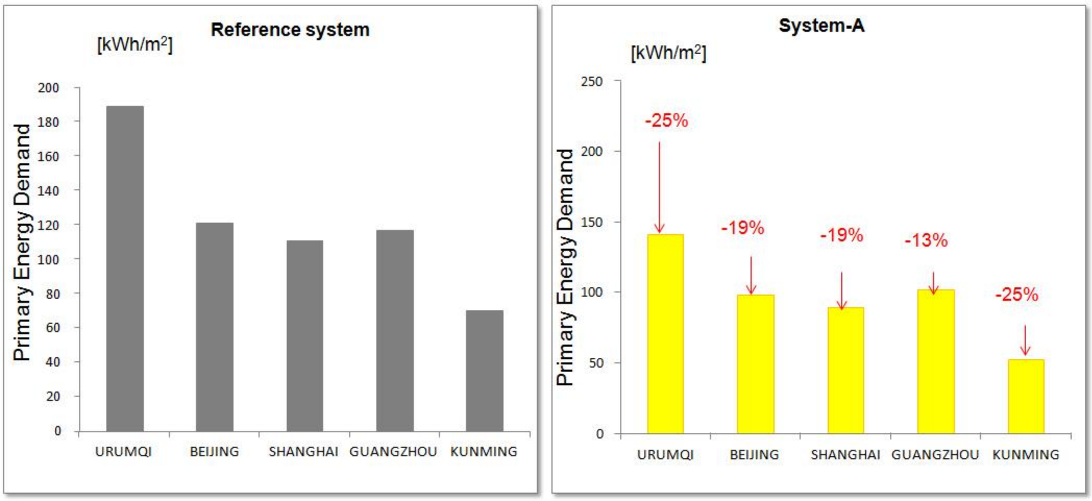


Fig 4.2.13 Yearly primary energy saved by system-A

4.2.1.6. Economic Analysis

In service life, total cost of building service system consists of two parts, which are investment and yearly operating cost.

Investment

In reference systems, heat radiator and air-conditioner are main investments for space heating/cooling in district-heating cities. In no district-heating cities, reversible air-conditioner is main investment. Gas water-heater is also part of system investment. In this thesis, investments for lighting and appliance among different systems are supposed to be the same. Fig 4.2.14 – Fig 4.2.17 indicate the composition of investments (reference system) in each flat.

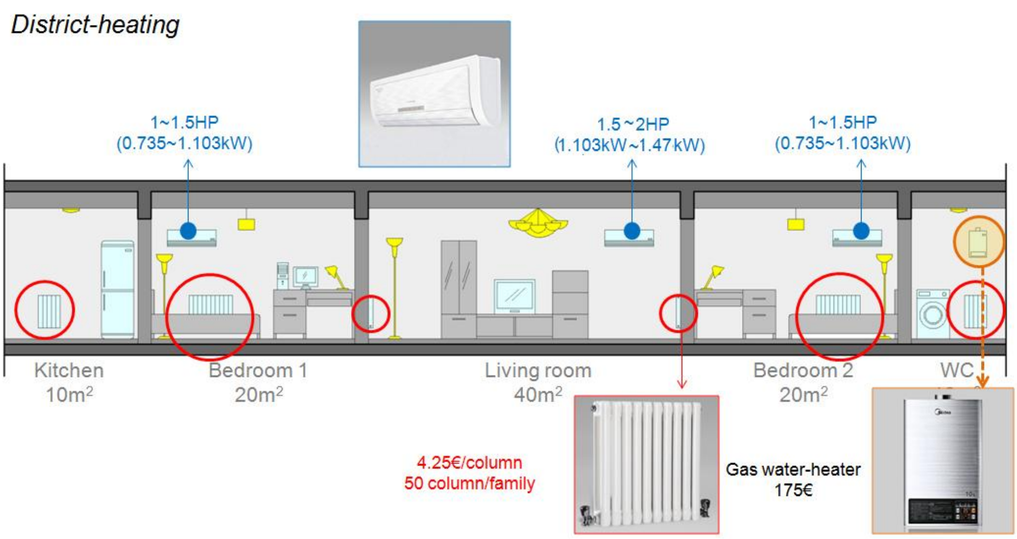


Fig 4.2.14 Investment for Reference system in one flat (district-heating)

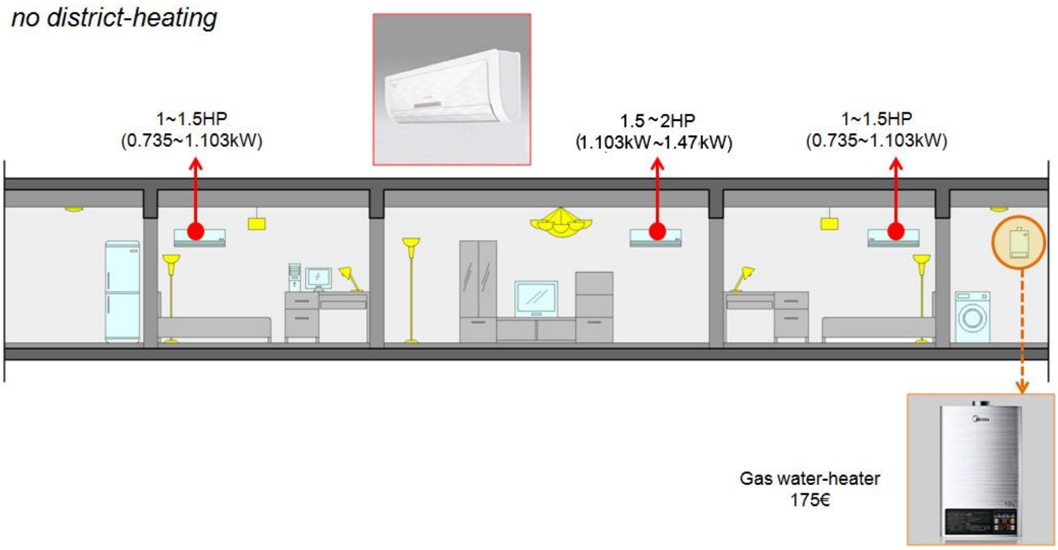


Fig 4.2.15 Investment for Reference system in one flat (no district-heating)

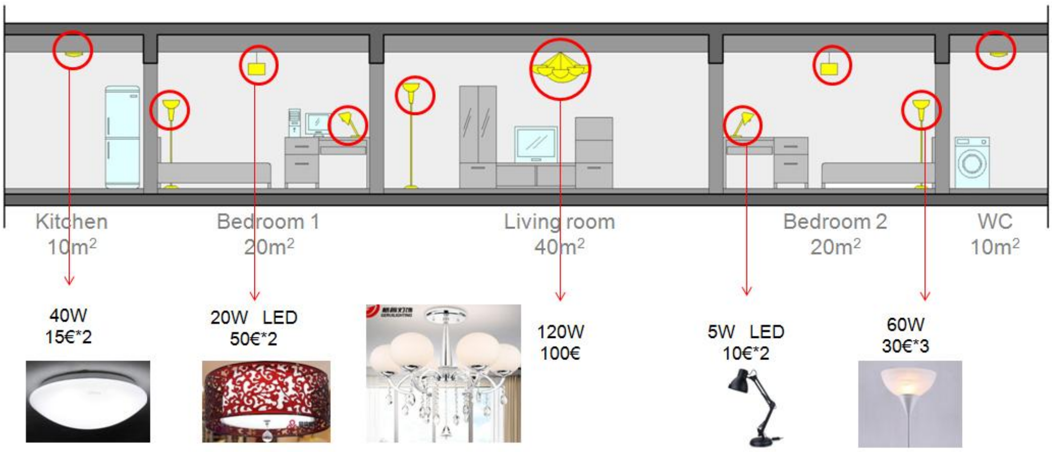


Fig 4.2.16 Investment for lighting in one flat

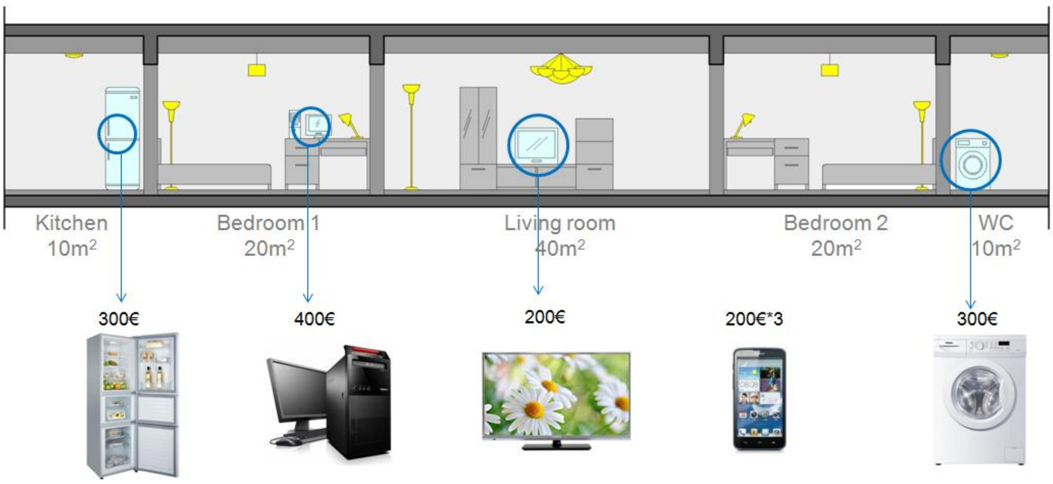


Fig 4.2.17 Investment for appliances in one flat

		URUMQI	BEIJING	SHANGHAI	GUANGZHOU	KUNMING
Domestic hot water [€/flat]	gas water-heater	200	200	200	200	200
Space heating [€/flat]	heating radiator	200	200			
	reversible air conditioner			1200	1300	1100
Space cooling [€/flat]	air conditioner	1000	1000	as above	as above	as above
Lighting + Appliance [€/flat]		2200	2200	2200	2200	2200
total [€/flat]		3600	3600	3600	3700	3500
total [€/m^2]		36	36	36	37	35

Table 4.2.4 Investment for reference system in each city

According to literatures [16] and report [17] from Chinese environmental protection ministry, the average investment for solar thermal system in China is about 200€/m$^2_{collector}$ including solar collector, thermal storage, pipes and floor heating.

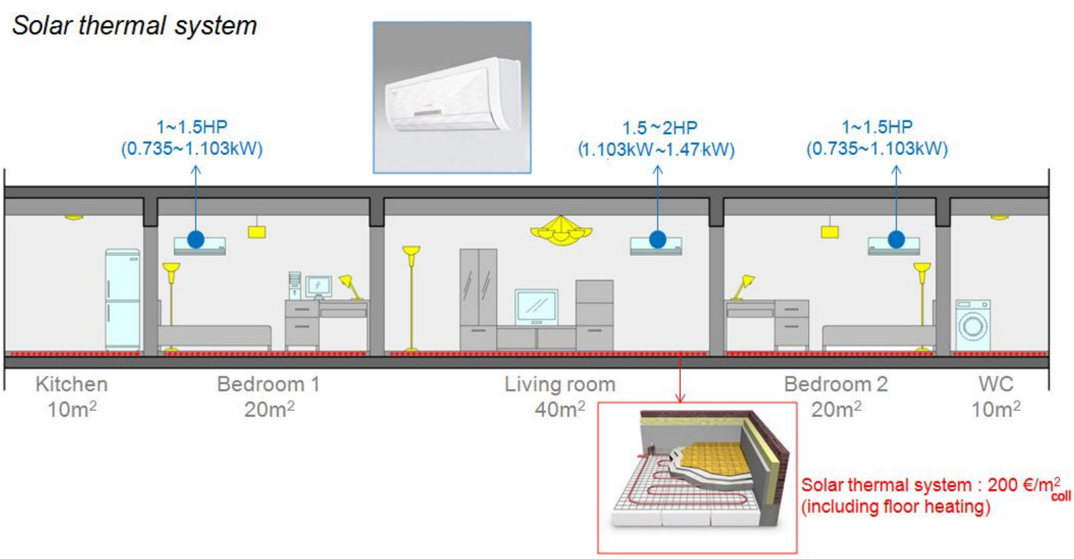


Fig 4.2.18 Investment for system-A in one flat

Investment for system-A is shown as table 4.2.5.

		URUMQI	BEIJING	SHANGHAI	GUANGZHOU	KUNMING
area of solar collectors [m^2/building] (108 flats / building)		240	360	360	480	480
DHW + SH [€/flat]	solar system	450	650	650	900	900
COOLING [€/flat]	air conditioner	1000	1000	1100	1200	1000
LIGHTING+APPLIANCE [€/flat]		2200	2200	2200	2200	2200
total [€/flat]		3650	3850	3950	4300	4100
total investment [€/m^2]		37	39	40	43	41

Table 4.2.5 Investment for system-A

System investment could be borrowed from bank and paid back regularly as annuity (yearly capital cost). The factor of annuity (ANF) is depending on time period (n) and interest rate (i).

$$ANF_{n,i} = \frac{(1+i)^n \times i}{(1+i)^n - 1} \qquad (17)$$

ANF = factor of annuity
n= time period [a]
i = interest rate [%/a]

In this thesis, 20 years is supposed to be the service life of building technologies. Interest rate is 6.55%/a. According equation (17), annuity is 9%/a of investment.

Yearly capital cost [€ /(m^2a)]	URUMQI	BEIJING	SHANGHAI	GUANGZHOU	KUNMING
system REF	3.3	3.3	3.3	3.4	3.2
system-A	3.4	3.6	3.6	3.9	3.7

Table 4.2.6 Yearly capital cost in each city

Operating cost

Yearly operating cost has also two parts, which are energy cost and maintenance cost. Yearly maintenance cost is supposed to be 1% of system investment. Yearly energy cost increases because of the increasing energy price (Table 4.2.7). Fig 4.2.19 indicates yearly payment of system-A in Shanghai.

Fuel Type	Price
gas	0.025€/kWh
coal	0.009€/kWh
gas	0.025€/kWh
electricity	0.075€/kWh

Table 4.2.7 Fuel price in China (2010)

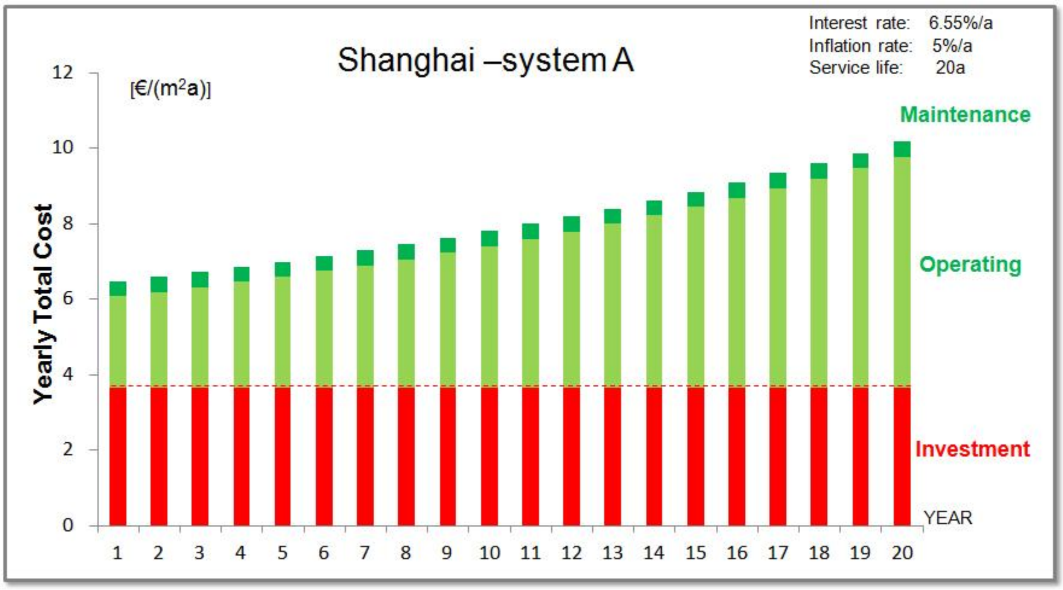


Fig 4.2.19 Yearly payment of system-A in Shanghai

As shown in Fig 4.2.20, though the investment for system-A is higher than reference system, the total cost in service life (20a) is lower.

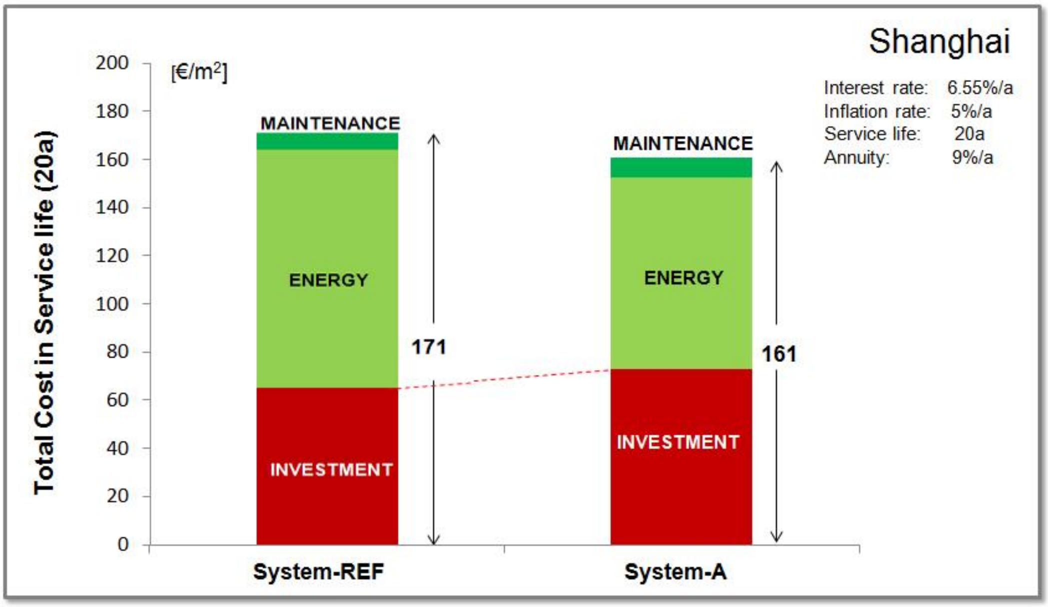


Fig 4.2.20 Total cost in service life

In district-heating area of China, heating cost is paid according to the floor area instead of the real energy consumption. It is about 2.13€/(m^2a) (coal as fuel) and 3.75€/(m^2a) (gas as fuel). Supply temperature and operating period are central controlled. Residents could not adjust it individually. There is a big amount of energy waste because of "over heating the room". This situation is changing now. Chinese government will install metering device and temperature controller in each flat. District-heating cost will be paid according to the real energy consumption in each flat. Based on the fuel price in 2010 (Table 4.2.7), yearly energy cost of reference system and system-A in each city are shown as Fig 4.2.21. Energy cost of system-A is lower than reference system in these cities (except Urumqi).

In Urumqi, the fuel of district-heating is coal, which is very cheap. However, in System-A, gas is the auxiliary energy source. The price of gas is 0.03€/kWh , which is nearly 3 times of coal price. Though energy demand of system-A is lower than reference system, the energy cost of system-A is higher.

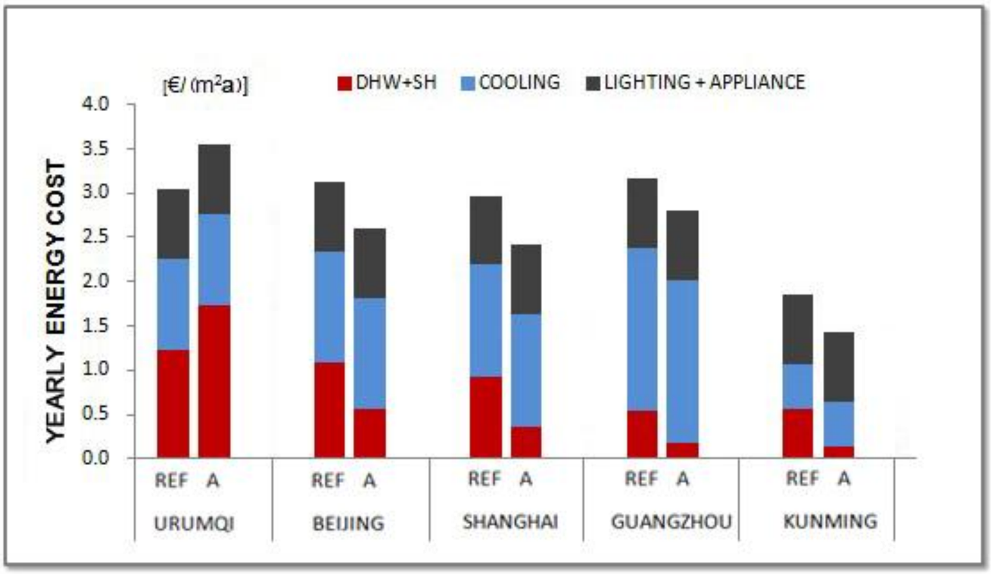


Fig 4.2.21 Yearly energy cost of system-A

Fig 4.2.22 Total cost in service life of reference system and system-A

Fig 4.2.22 shows the total cost (investment and operating cost) of system-A and reference system in service life (20 year). In Beijing and Shanghai, the total cost of system-A is lower than reference system. In Guangzhou and Kunming, where heating demand is not dominant, the advantage of system-A is not significant.

Compared with reference systems, 13% up to 25% primary energy demand could be reduced in system-A. In service life of system (20a), total cost of system-A is lower than that of reference systems in Beijing and Shanghai. In Guangzhou and Kunming, where heating demand is very low, total costs of both systems are similar. In Urumqi, cost of system-A is a little higher than reference system because of the cheap price of coal.

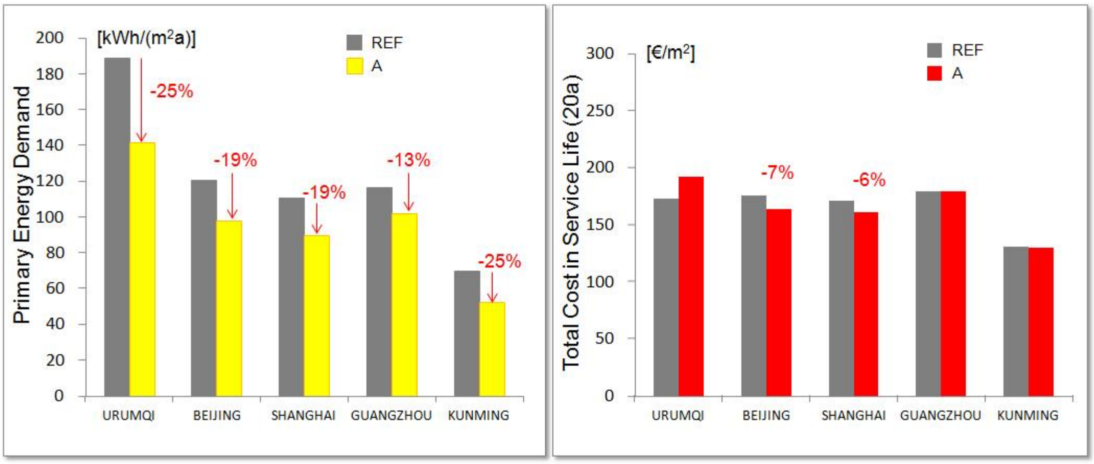


Fig 4.2.23 Comparison between reference system and system-A

According to the discussion in this Chapter, using solar thermal system for space heating and domestic hot water could save both primary energy and total cost in service life. It is proved to be a suitable building service technology in China for energy efficient residential buildings.

4.2.2. Ground-Coupled Heat Pump System (GCHP)

4.2.2.1. Energy saving potential

Electrical air-conditioner is the most popular cooling equipment in Chinese residential buildings. It works as air-source heat pump. Reversible air-conditioner is also used for heating, especially in hot summer and cold winter zone. However, seasonal performance factor (SPF) of air-source heat pump is low in winter, because the temperature difference between indoor and outdoor is very large (Chapter 3.3.2).

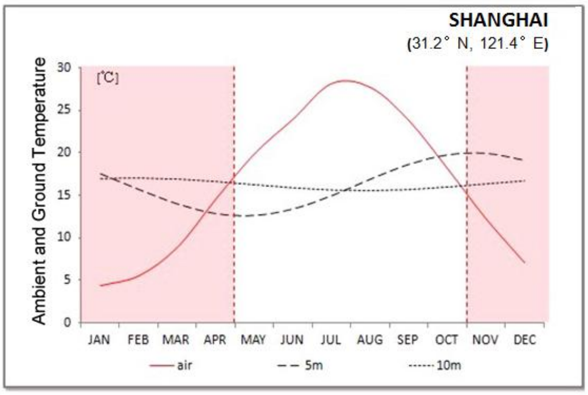


Fig 4.2.24 Air temperature and underground temperature

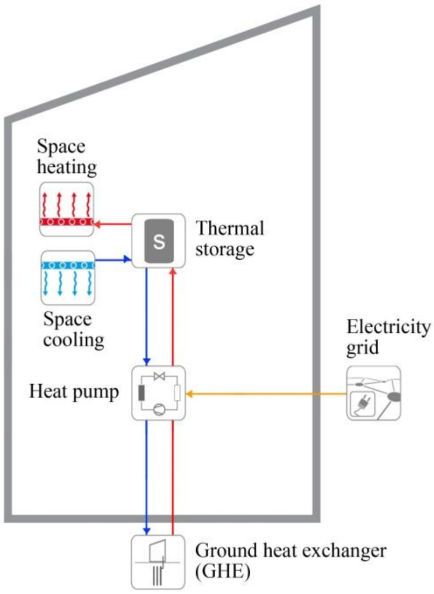


Fig 4.2.25 GCHP system

During the year, temperature fluctuation underground is smaller than the air. Soil temperature is close to the yearly average air temperature when it is deep enough. Take Shanghai for example, the soil temperature at 10 m depth is constant at 16℃, which is the yearly average air temperature. Compared with air-source heat pump, ground-coupled heat pump system has smaller temperature difference between heat source and heat sink. It could achieve higher Coefficient of Performance (CoP) (Chapter 3.3.2). It is more suitable to supply space heating in the building.

Fig 4.2.25 indicates the design of a typical GCHP system. Radiant floor is suitable in GCHP system because of the narrow temperature difference between supply and return. In heating period, heat is delivered from soil into room by Ground-coupled heat pump (GCHP). In cooling period, the direction is reversed.

4.2.2.2. Simulation of GCHP system

GCHP system for the basic model is simulated in software "Trnsys". Building data are the same as basic model (Chapter 2.2.1). Installed capacity of heat pump is calculated according to heating and cooling load of the basic model (Table 4.2.8). It is supposed to cover 80% of peak load.

peak load	Heating [W/m^2]	cooling [W/m^2]
URUMQI	43	45
BEIJING	33	46
SHANGHAI	23	38
GUANGZHOU	11	51
KUNMING	16	30

Table 4.2.8 Heating and cooling load of basic model (600 m^2×18 floors)

According to simulation results, electricity demand of GCHP is shown as Fig 4.2.26.

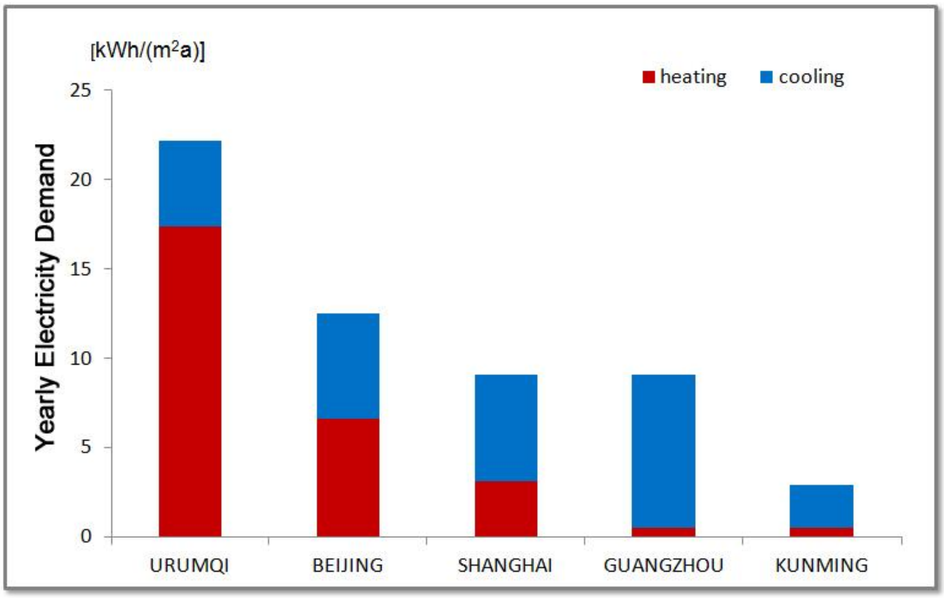


Fig 4.2.26 Yearly electricity demand of GCHP

4.2.2.3. Overall building service system

To compare with other building service systems, total primary energy demand of overall building service system should be discussed. In system-B, space heating and cooling are supplied by GCHP. Domestic hot water is served by electric water-heater (ŋ=0.8). Other settings, such as lighting and appliances are the same as reference systems (Chapter 2.2.2) and system-A (Chapter 4.2.1.5). Fig 4.2.27 indicates the construction of system-B.

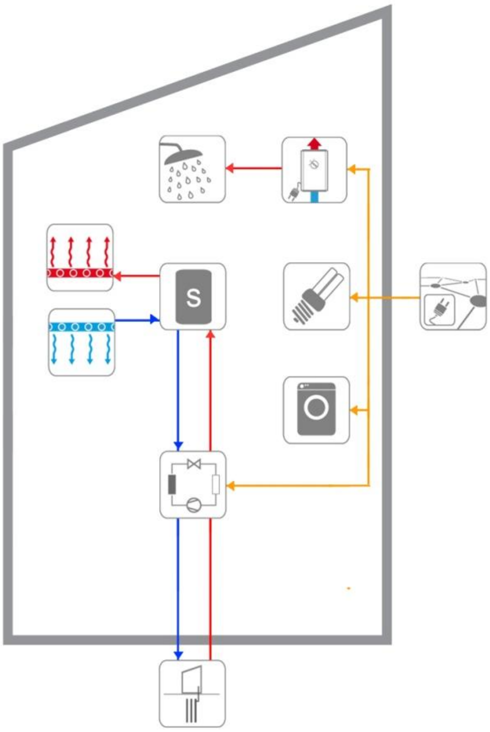


Fig 4.2.27 Building service system-B

Based on the PE-factor of electricity (PE=2.7), the yearly primary energy demand in each city could be calculated.

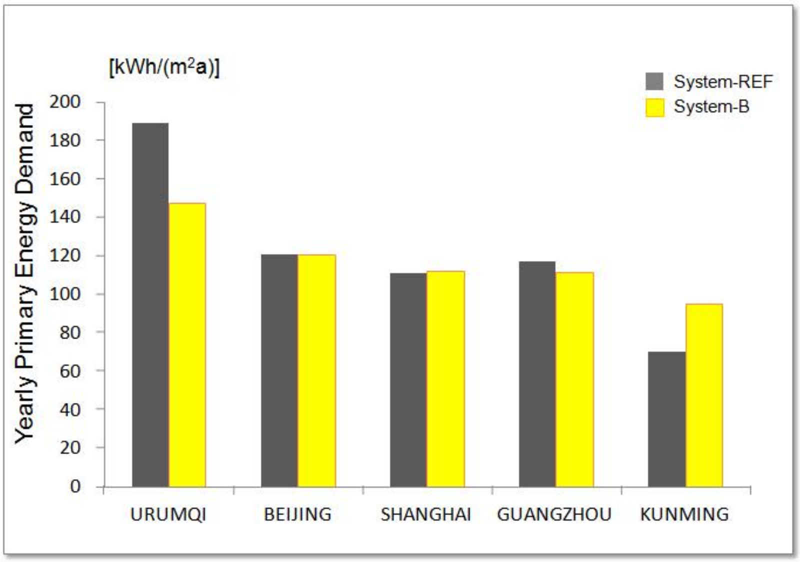


Fig 4.2.28 Primary energy demand

Compared with reference systems, system-B has no advantage in energy saving. It is because of the low efficiency of electric water-heater and high PE-factors of its energy source (electricity). In reference systems, domestic hot water is heated by gas water-heater, whose efficiency is 0.9. PE-factor of gas is 1.1. In system-B, domestic hot water is supplied by electric water-heater. Efficiency of this system is 0.8, which is as low as gas water-heater. However, PE-factor of its energy source (electricity) is 2.7, which is nearly three times of gas (Fig 4.2.29). In order to reduce primary energy demand, system-B is transformed into system-C.

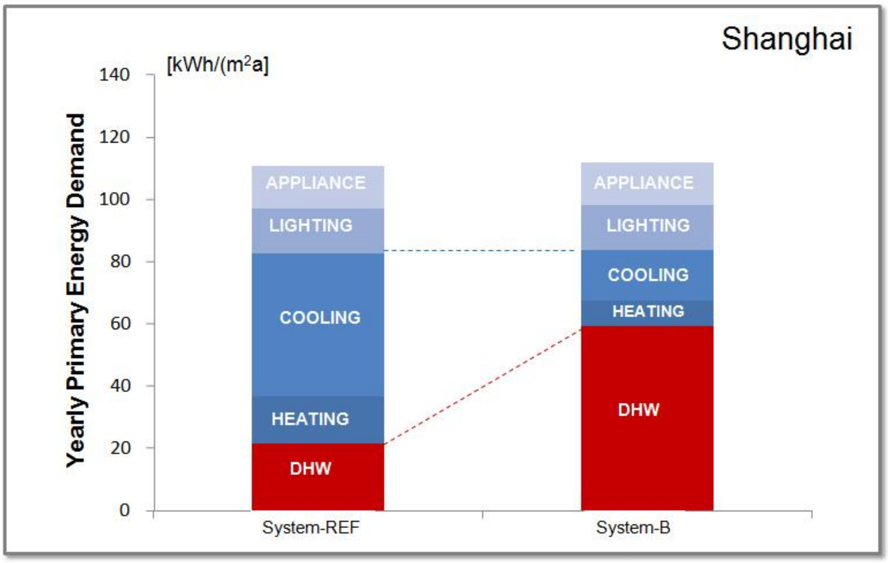


Fig 4.2.29 Yearly primary energy demand of reference system and system-B

4.2.2.4. Air-source heat pump

In system-C (Fig 4.2.30), domestic hot water is supplied by air-source heat pump instead of electric water-heater. In summer, seasonal performance factor (SPF) of air-source heat pump could be 3.5 or higher. However, in winter the SPF of air-source heat pump is reduced to 2.5 or lower. “SPF=2.8” could be taken as average value during the year. The energy balance of system-C is shown as Fig 4.2.31.

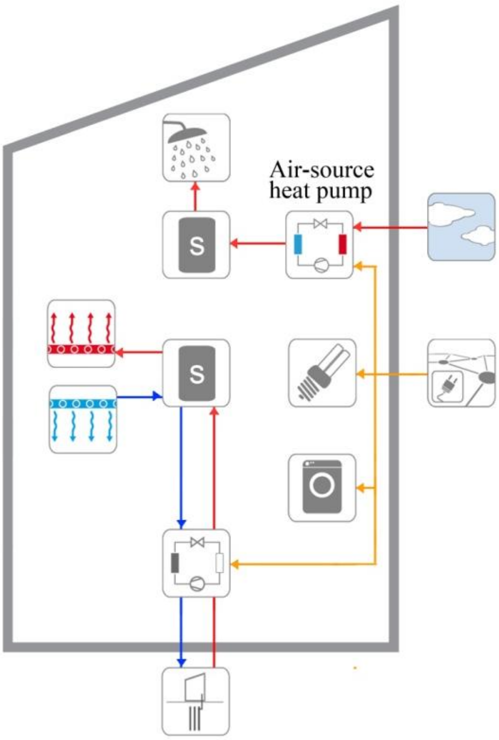


Fig 4.2.30 Building service system-C

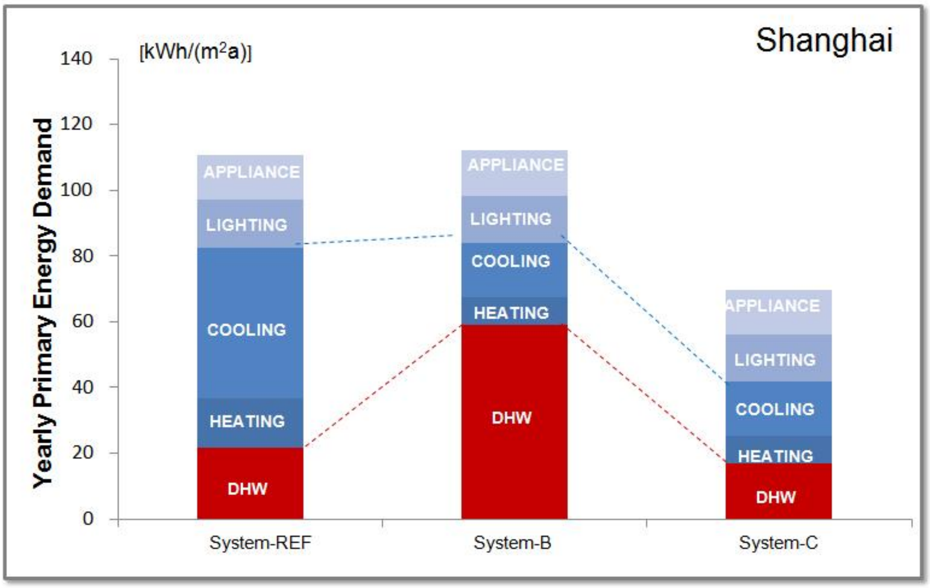


Fig 4.2.31 Yearly primary energy demand in Shanghai

Compared with reference systems, primary energy demand could be 24% up to 44% reduced in system-C.

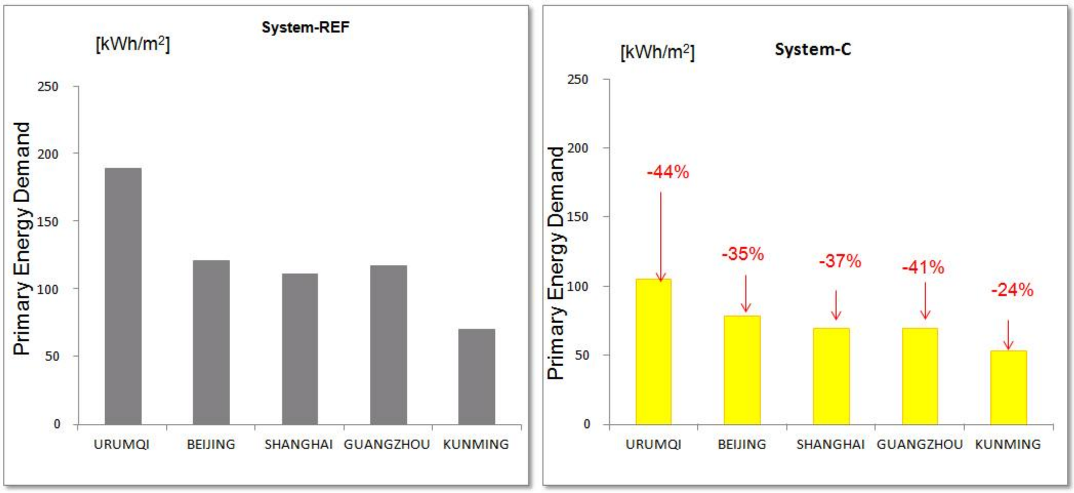


Fig 4.2.32 Primary energy saved by system-C

4.2.2.5. System-C with PV system

System-C could also be improved by using Photovoltaic (PV) system to generate electricity locally. In system-D (Fig 4.2.33), the roof area of basic model is used for PV module. Electricity produced by PV Array will feed back to public electricity grid. Space heating and cooling are supplied by GCHP system. Domestic hot water is heated by air-source heat pump as in system-C.

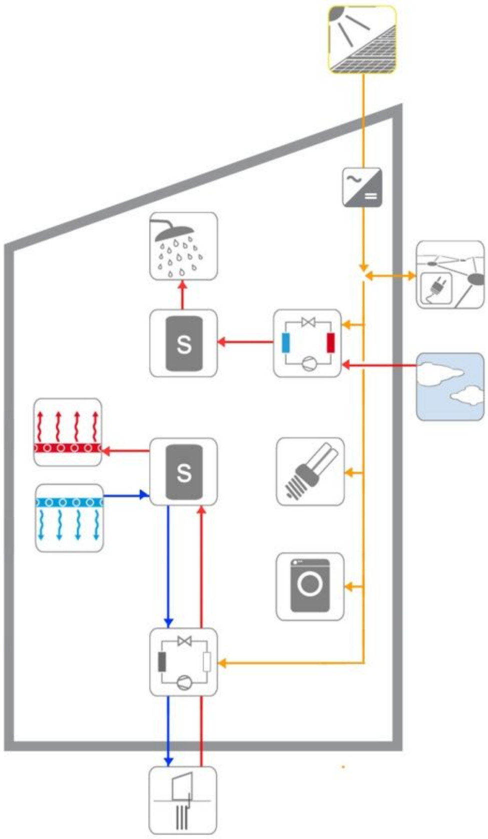


Fig 4.2.33 Building service system-D

PV system for basic model is simulated in the software “PV*SOL Expert 5.5”. Characteristic of PV module is shown as Fig 4.2.34.

PV module “BP 4175T”

Maximum power (P_{max})	175W
Voltage at Pmax (V_{mpp})	35.4V
Current at Pmax (I_{mpp})	4.94A

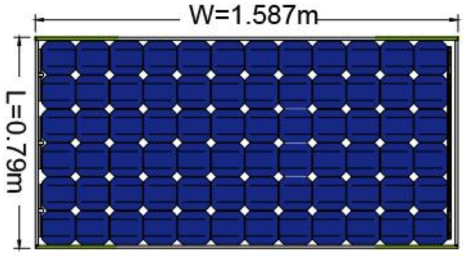


Fig 4.2.34 Characteristic of PV module “BP 4175T”

	URUMQI	BEIJING	SHANGHAI	GUANGZHOU	KUNMING
Latitude [°]	43.83	39.8	31.17	23.13	25.02
tilt angle [°]	45	40	30	25	25
number of PV module	185	222	296	333	333
PV output [kW_P]	32	39	52	59	59

Table 4.2.9 Data of PV modules on the roof

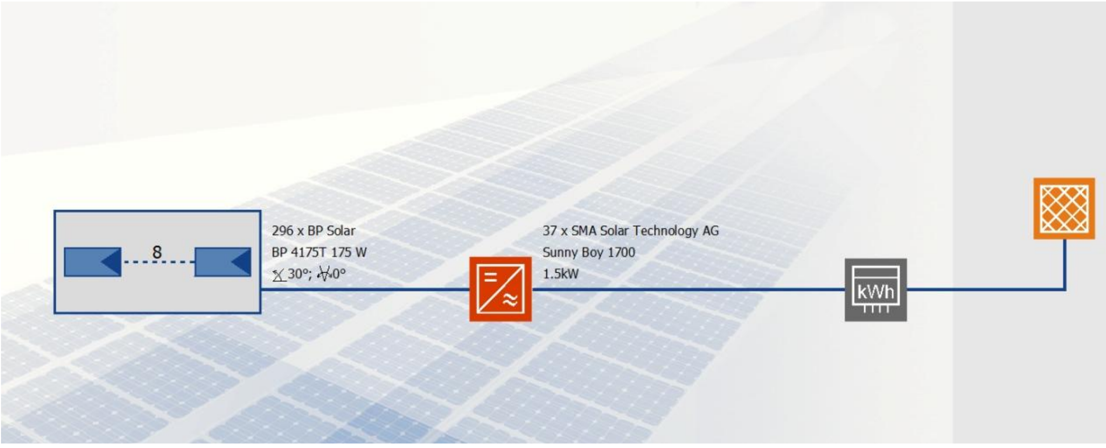


Fig 4.2.35 PV system simulated in “PV*SOL Expert 5.5” (Shanghai)

Fig 4.2.36, Fig 4.2.37 and Fig 4.2.38 show simulation results. According to the simulation, 42 up to 75 MWh/a electricity are produced by PV system each year. It is about 950 up to 1350 kWh/kW$_p$ (Fig 4.2.36), which are higher than that in Germany (2013). This amount of PV electricity could cover 10% up to 35% of total electricity demand among these cities (Fig 4.2.37).

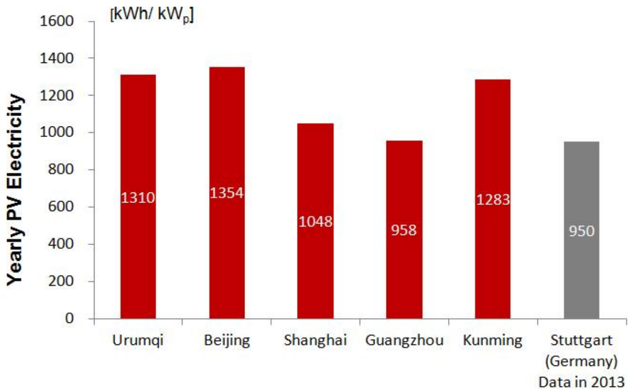


Fig 4.2.36 Yearly PV electricity among different cities

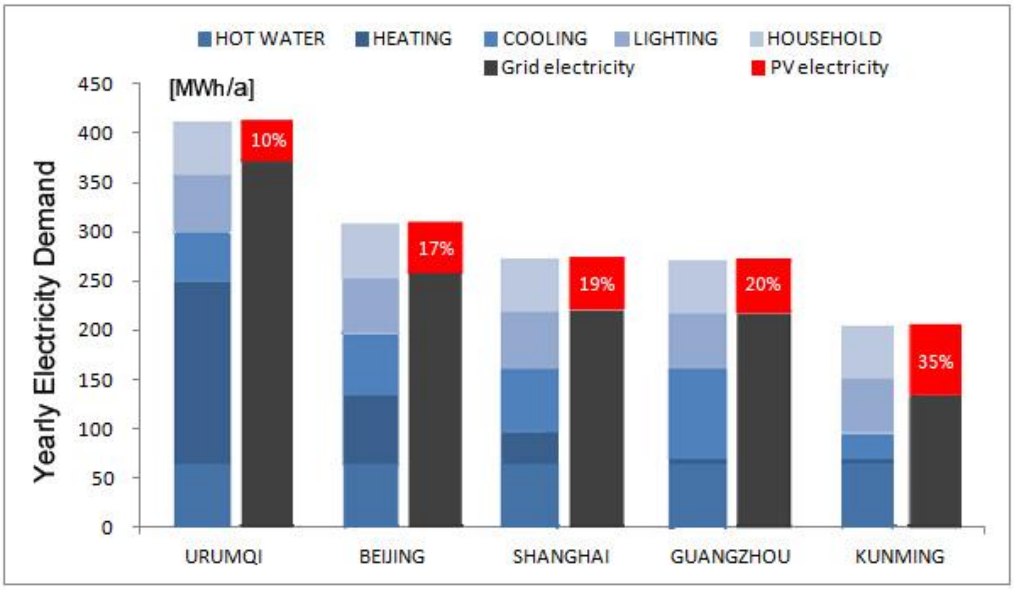


Fig 4.2.37 Electricity balance of system-D

Compared with reference systems, primary energy demand could be 46% up to 53% reduced in these cities.

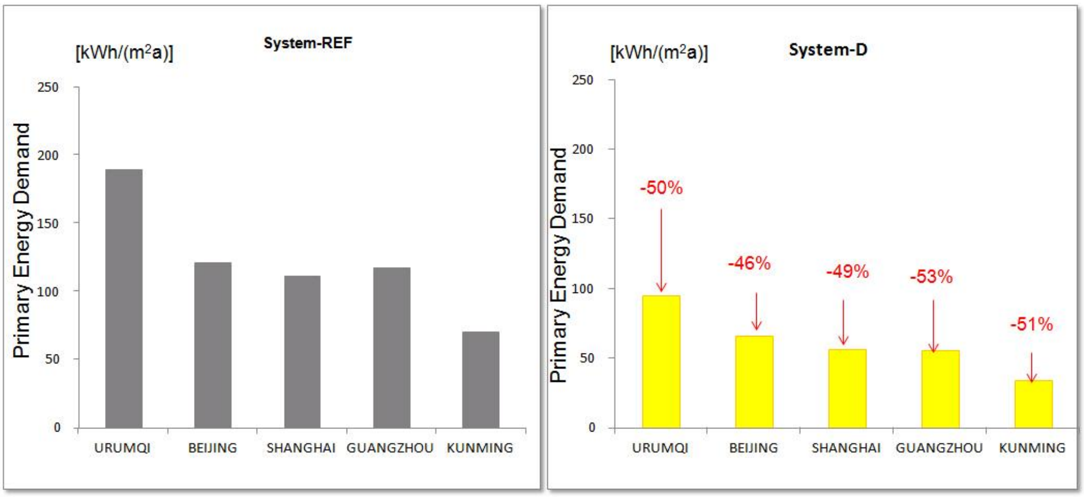


Fig 4.2.38 Primary energy saved by system-D

4.2.2.6. Economic Analysis

Investment

In system-B, investment for space heating/cooling and domestic hot water in one flat is shown as Fig 4.2.39.

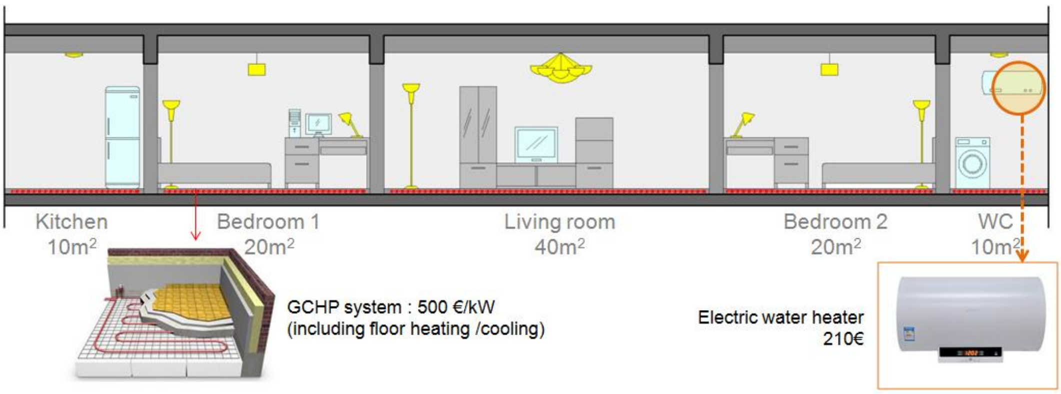


Fig 4.2.39 Investment for heating, cooling and DHW in one flat (system-B)

According to information from Chinese environmental protection ministry, the average investment for

GCHP system in China is about 500 €/kW, including heat pump, ground-heat exchanger, pipes and floor heating (cooling) system. Investment for system-B could be shown as Fig 4.2.40.

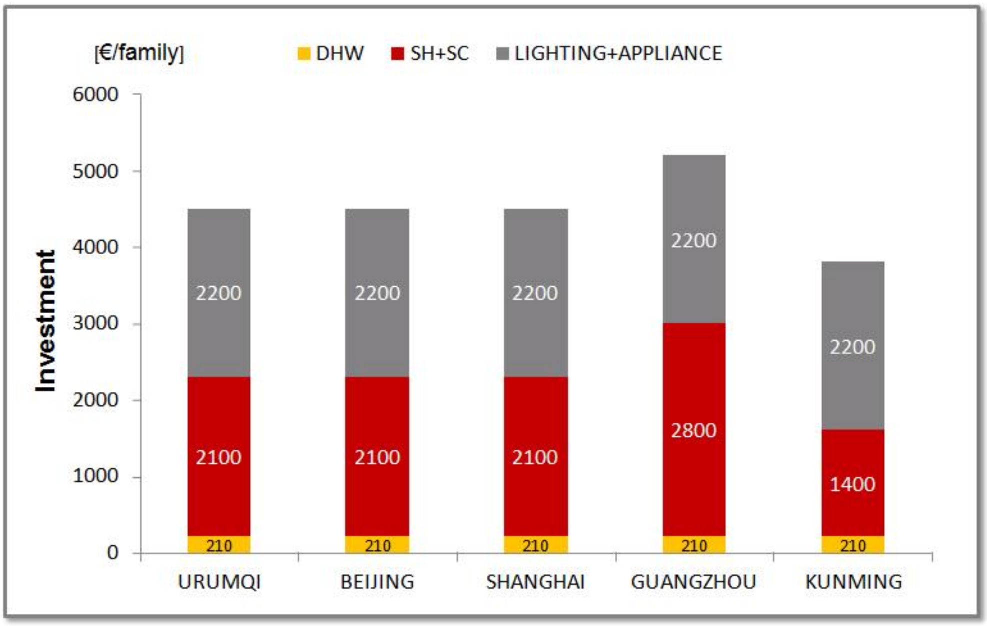


Fig 4.2.40 Investment for system-B

In system-C, domestic hot water is supplied by air-source heat pump instead of electric water-heater. The investment for air-source heat pump (50 kW) is about 10000€ for this building (108 flats), which is cheaper than electric water-heater.

According to the literature "Cost, price and technology advantage of PV in China" [18] and information from Chinese environmental protection ministry, the average investment for PV system (on roof) in China is about 2600€/kW$_P$ (Data in 2010). Investment for system-D could be shown as Fig 4.2.41.

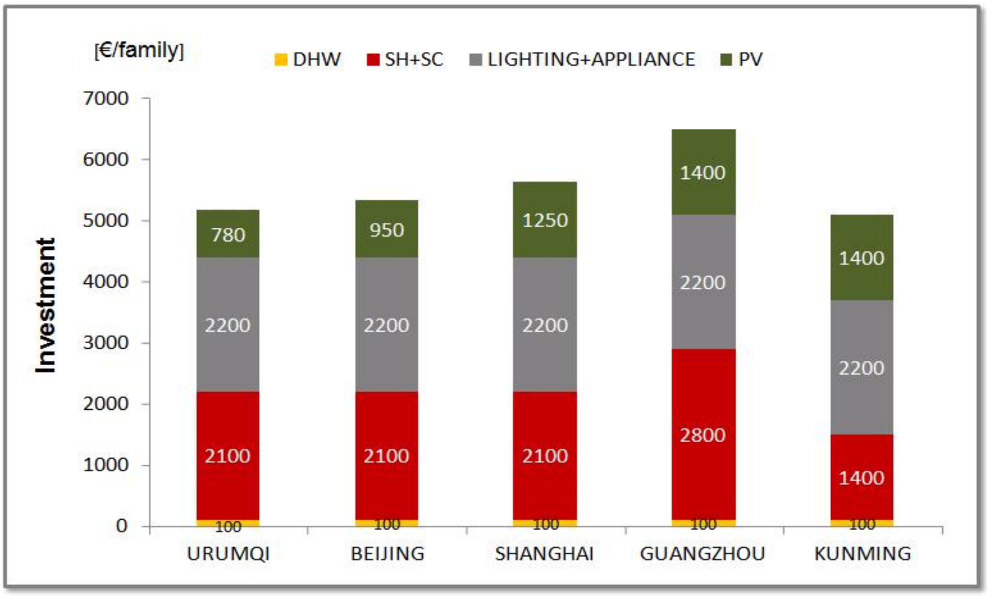


Fig 4.2.41 Investment for system-D

Yearly energy cost

Based on the energy price in 2010, yearly energy cost of reference system, system-B and system-C are indicated as Fig. 4.2.42. Compared with reference system, the cost for domestic hot water in system-B is much higher. It is because that the fuel price of water-heater in system-B (electricity) is much higher than that in reference systems (gas/coal). In the year 2010, electricity price is 0.08€/kWh, which is about 3 times of gas (0.03€/kWh) and 8 times of coal (0.01€/kWh).

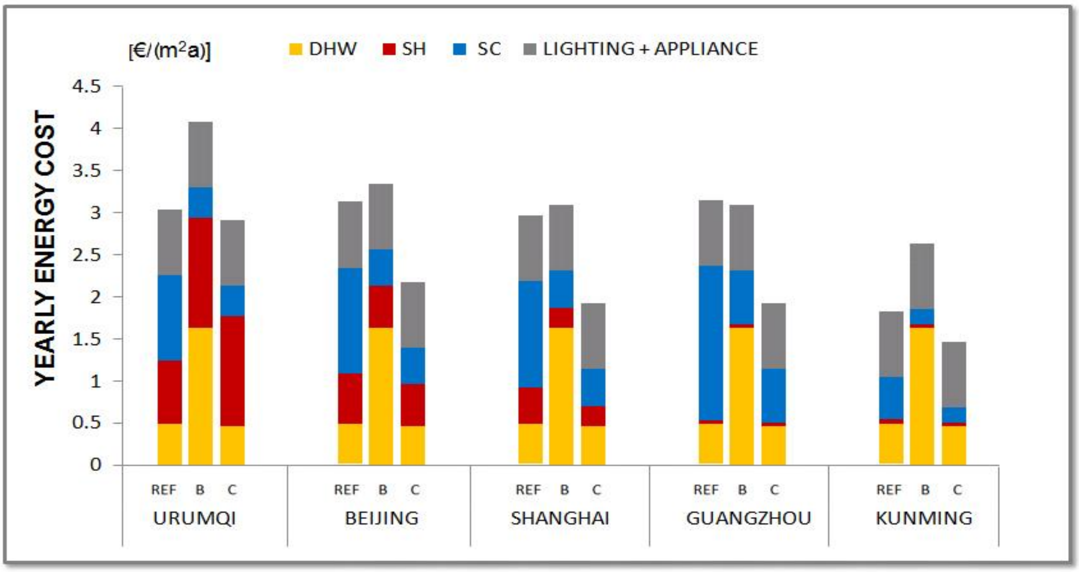


Fig 4.2.42 Yearly energy cost

In system-D, PV electricity could be sold to electricity grid under the price 0.13 €/kWh (data in 2010). Yearly energy cost is shown as Fig 4.2.43. Because of the electricity generation, yearly cost of system-D is lower than that of system-C.

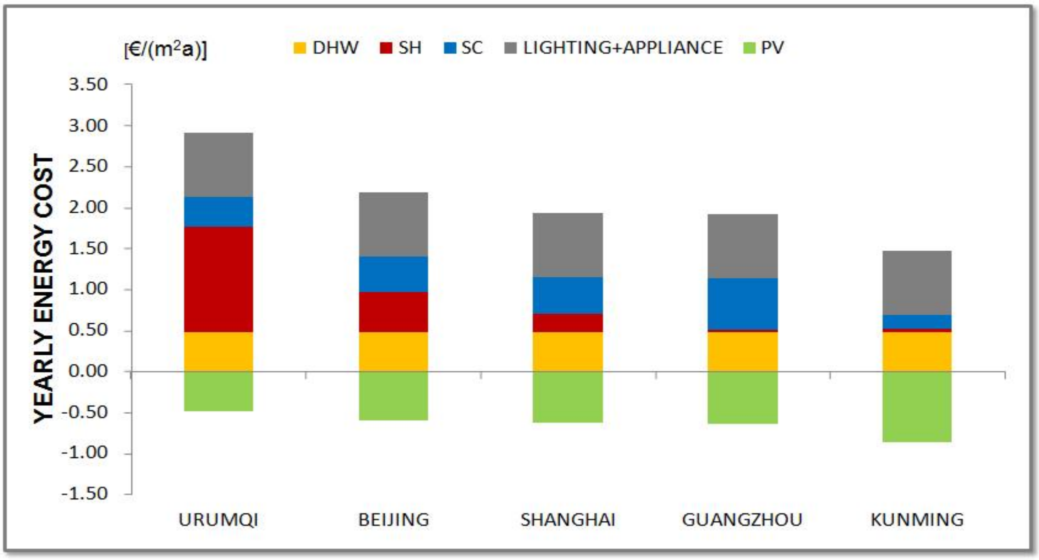


Fig 4.2.43 Yearly energy cost of system-D

4.2.3. System analysis

4.2.3.1. Comparison of systems

The following 4 advanced building service systems (Fig 4.2.44 and Fig 4.2.45) have been discussed in Chapter 4.2.1 and 4.2.2:

System-A:
Solar thermal systems for domestic hot water and space heating;
Air-conditioner for space cooling;
System-B:
Ground-coupled heat pump system for space heating and cooling;
Electric water-heater for domestic hot water;
System-C:
GCHP system for space heating and cooling;
Air-source heat pump system for domestic hot water;
System-D:
GCHP system for space heating and cooling;
Air-source heat pump system for domestic hot water;
PV modules on the roof for electricity generation

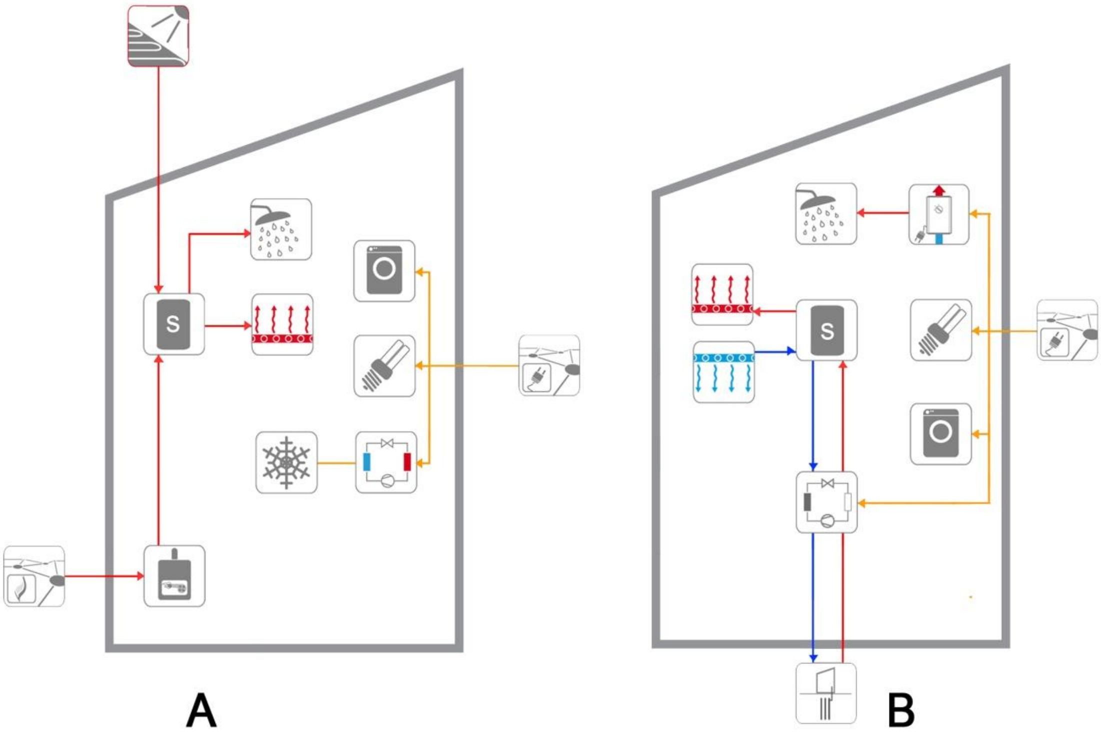


Fig 4.2.44 Advanced building heating and cooling systems (system-A and system-B)

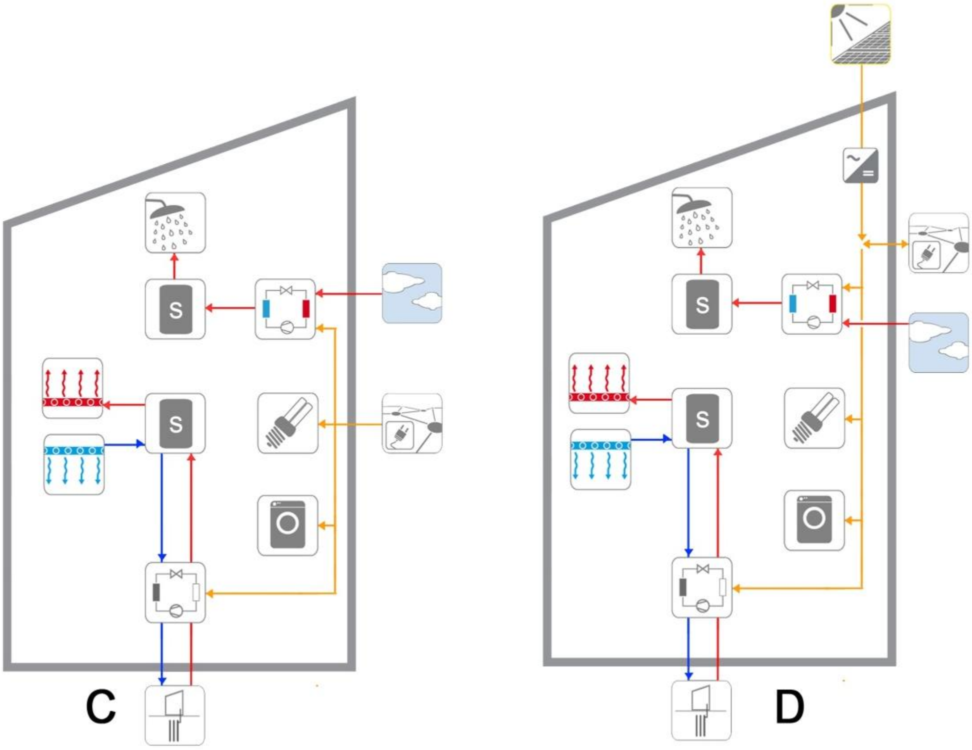


Fig 4.2.45 Advanced building heating and cooling systems (system-C and system-D)

Fig 4.2.46 shows primary energy demand of these systems. System-D has the lowest yearly primary energy demand. In the view of energy saving, the combination of GCHP and PV system could be the best choice in China.

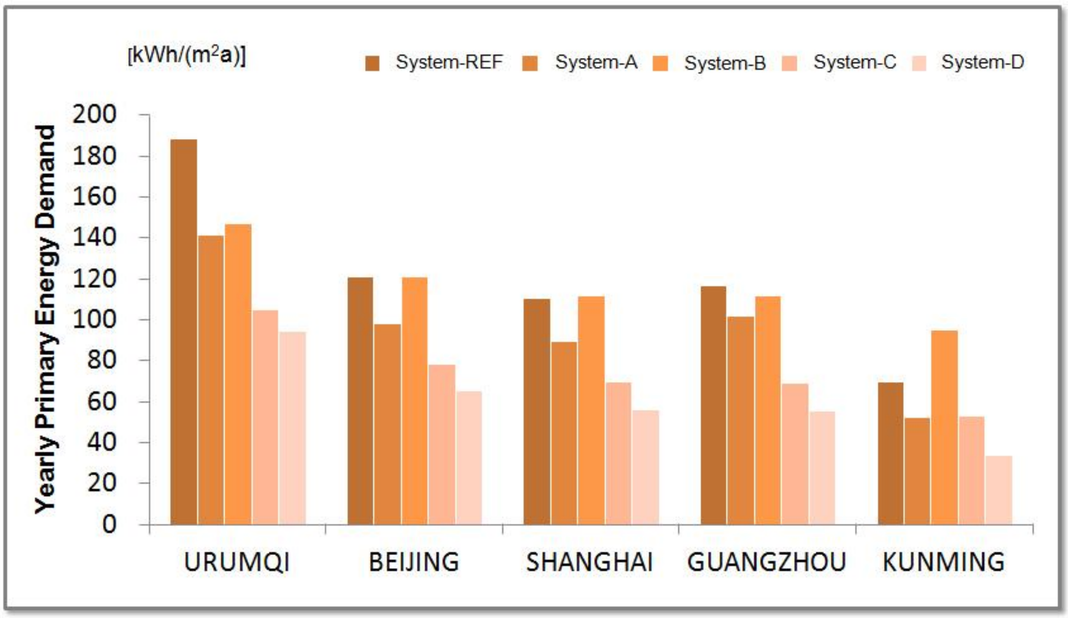


Fig 4.2.46 Yearly primary energy demand

The investment and yearly energy cost of each system are shown as Fig 4.2.47. System-D has the lowest energy cost among these systems. However, investment for system-D is the highest.

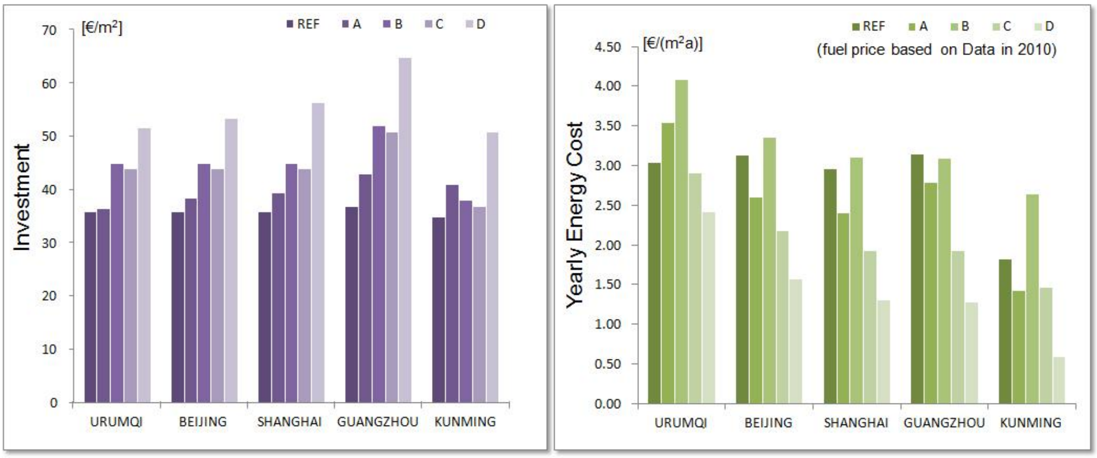


Fig 4.2.47 Investment and yearly energy cost

In service life (20a), total cost (investment and operating cost) of system-C is lower than any other systems (except in Urumqi) (Fig 4.2.48). With a consideration of actual cost, the combination of GCHP and air-source heat pump (system-C) could be the best choice in China.

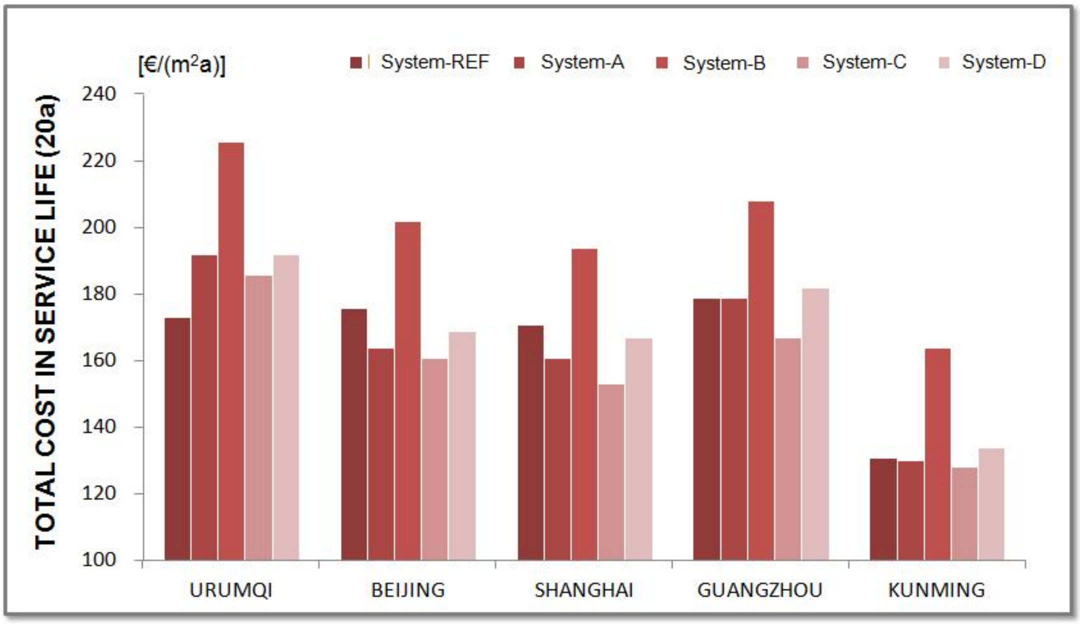


Fig 4.2.48 Total cost in service life (20a)

Since the year 2009, government financial support for PV systems has been carried out in China. According to the document “Financial fund for PV-Building [2009-129]”, 2.5€/W_P will be subsidized to buildings which are integrated with PV technology. According to that, the investment for system-D will be reduced. It makes system-D more competitive.

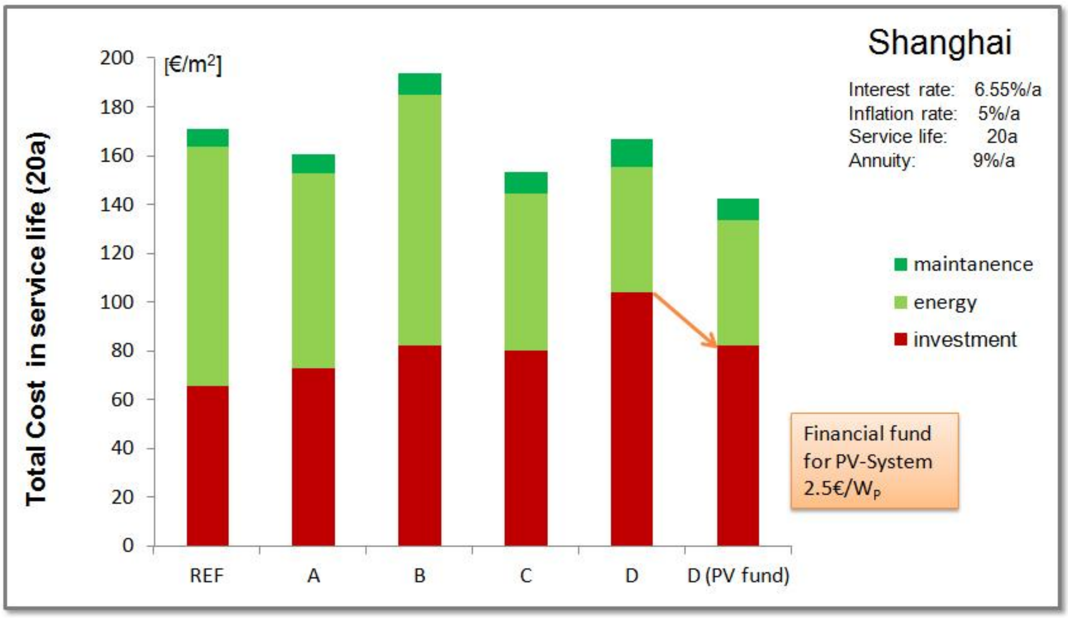


Fig 4.2.49 Total cost in service life (20a) in Shanghai

Take Shanghai as an example, when government financial support for PV systems is considered, total cost of system-D in service life (20a) could be 17% lower than that of reference system. The combination of GCHP system and PV system (system-D) could achieve the lowest total cost in these cities (except in Urumqi). Total cost of the reference system in Urumqi is lower than system-D, because the energy price of coal is much lower than electricity (Table 4.2.7).

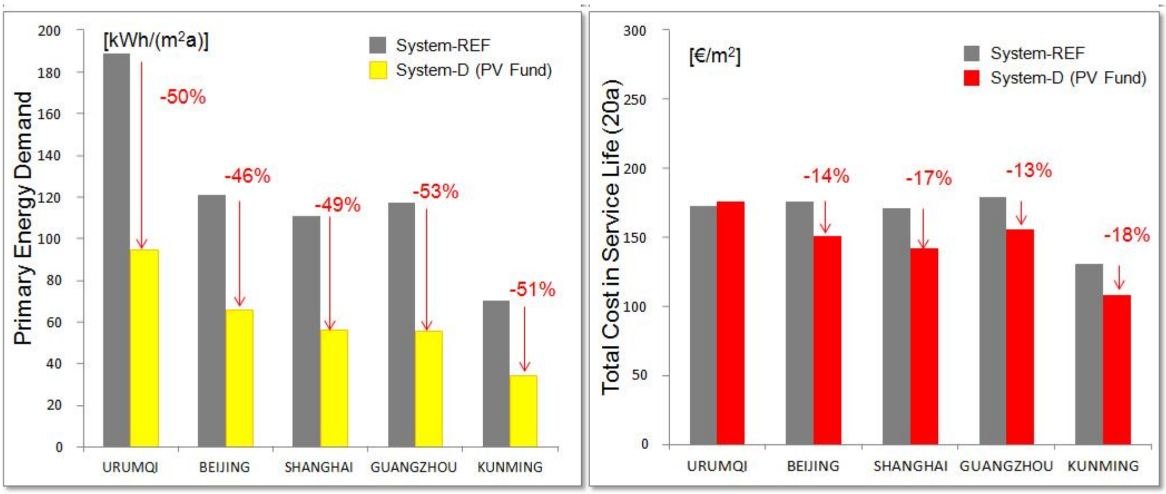


Fig 4.2.50 Comparison between reference system and system-D (with government fund)

Compared with the reference system, system-D could save 46% up to 53% of primary energy. With the consideration of financial subsidy, the total cost in service life (20a) of system-D could also be 13% up to 18% lower than reference system in Beijing, Shanghai, Guangzhou and Kunming. Among these building service systems, the combination of GCHP and PV system (system-D) is proved to be the most suitable building service system for multi-story residential buildings in China.

4.2.3.2. Conclusion

According to the discussion in Chapter 4.2, conclusion about building service systems could be listed as follow.

- ✧ Using solar thermal system (domestic hot water and space heating) instead of the reference system could reduce 13% up to 25% of primary energy demand. Total cost in service life (20a), which is including investment and operating cost, could also be reduced, except in Urumqi. Because of the cheap coal price, total cost of solar thermal system in service life is a little higher than reference system in Urumqi. Compared with “warm” cities (Guangzhou), solar thermal system is more suitable in “cold” cities (Beijing).

- ✧ Ground-coupled heat pump system (GCHP) could strongly reduce energy demand of space heating and cooling. However, the combination of GCHP and electric water-heater is not favorable under actual cost conditions in China. Both primary energy demand and total cost will be increased. Air-source heat pump could take the place of electric water-heater and serve domestic hot water. Compared with reference systems, the combination of GCHP (for space heating and cooling) and air-source heat pump (for domestic hot water) could reduce 24% up to 44% of primary energy demand. The total cost in service life (20a) is also lower. It is suitable for multi-story residential buildings in China.

- ✧ PV system could generate electricity and reduce energy cost in service life. The combination of GCHP system and PV system could reduce 46% up to 53% of primary energy demand. However, the investment for PV system is very high (data in 2010). With government financial support for PV system (2.5 €/W_P) , the combination of GCHP system and PV system could become the best solution for building service system in multi-story residential buildings in China.

4.3. Challenge and opportunity in the future

Shortage of energy and material resources is a worldwide problem. Compared with developed countries (Germany), energy supply in China has its own characteristics. With the development of economy and technology, Chinese energy-efficient multi-story residential buildings will face opportunity and challenge in the future.

4.3.1. Combined heat and power generation (CHP)

Combined heat and power generation (CHP) is simultaneous generation of usable heat and electricity in a single process (Fig 4.3.1). The heat, which is produced in the process of electricity generation could be recovered and used for space heating.

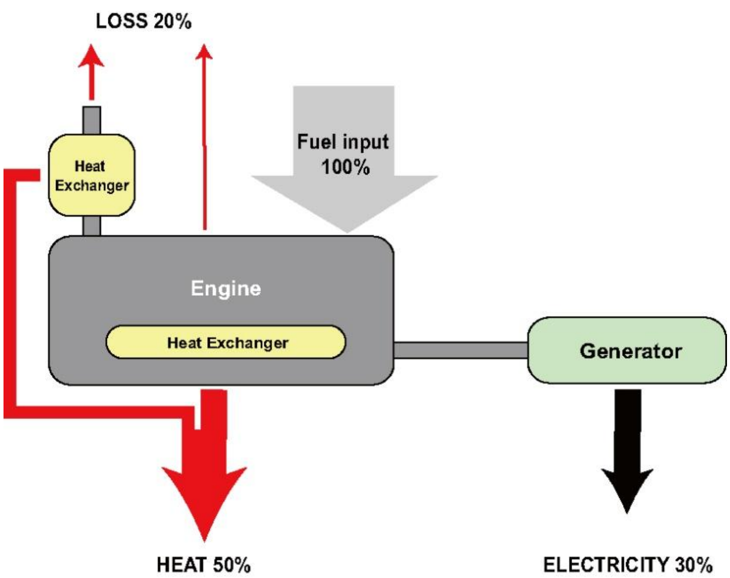


Fig 4.3.1 Combined heat and power generation (CHP)

Compared with the conventional way, CHP has higher efficiency and lower CO_2 emission to generate electricity and heat together. The efficiency of heat generation and electricity generation are about 50% and 30%, respectively. It is an ideal solution for district-heating system. In Germany, CHP has already widely used. Take the city Braunschweig for example, according to data from BS energy (bs-energy.de), about 97.1% of their district-heating is supplied by CHP plant. In China, the proportion of CHP in district heating is still lower than 50%.

If district-heating in China is also supplied by CHP as in Germany, primary energy demand could be reduced. Generally speaking, 1 kWh fuel input could produce about 0.3 kWh heat and 0.5 kWh electricity by CHP (Fig 4.3.1). Take Urumqi for an example, in order to produce 648 MWh/a heat (heating demand of the whole building), 1296 MWh/a fuel (gas) will be consumed. At the same time, 389 MWh/a electricity could be generated simultaneously. It will cover part of electricity demand. Primary energy demand of overall system in Urumqi is shown as Table 4.3.1.

		Final energy demand	Primary energy demand
Space heating	CHP (gas, PE-factor: 1.1)	1296 MWh/a ÷10800 m^2= 120 kWh/(m^2a)	120 kWh/(m^2a) ×1.1= 132 kWh/(m^2a)
Space cooling	Air conditioner (electricity, PE-factor: 2.7)	14 kWh/(m^2a)	14 kWh/(m^2a) ×2.7= 38 kWh/(m^2a)
DHW	Gas boiler (gas, PE-factor: 1.1)	20 kWh/(m^2a)	20 kWh/(m^2a) ×1.1= 22 kWh/(m^2a)
Lighting	(electricity, PE-factor: 2.7)	5.3 kWh/(m^2a)	5.3 kWh/(m^2a) ×2.7= 14 kWh/(m^2a)
Appliances	(electricity, PE-factor: 2.7)	5.1 kWh/(m^2a)	5.1 kWh/(m^2a) ×2.7= 14 kWh/(m^2a)
electricity from CHP		389 MWh/a ÷10800 m^2= 36 kWh/(m^2a)	36 kWh/(m^2a) ×2.7= 97 kWh/(m^2a)
Total			132+38+22+14+14-97= 123 kWh/(m^2a)

Table 4.3.1 Energy balance in Urumqi (CHP district-heating)

Compared with reference systems, total primary energy demand could be 30% reduced in Urumqi and 11% reduced in Beijing by using CHP (Fig. 4.3.2). Combined heat and power generation (CHP) is proved to be a good choice for Chinese district-heating in the future.

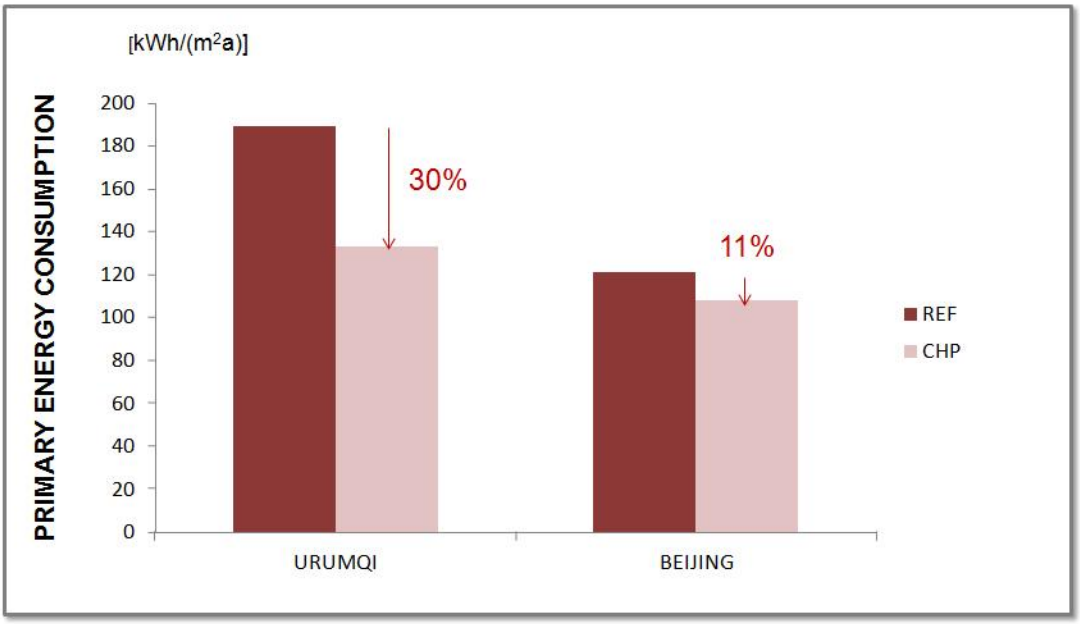


Fig 4.3.2 Total primary energy demand

4.3.2. Reduced price of PV module

The investment for PV system consists of four parts (Fig 4.3.3). PV module is the most costly part in PV system. With the development of PV technology in China, the price of PV module decreases dramatically. According to data from “ENF Solar”, the price of PV module has been reduced from 2.83€/W_P (2008) to 0.46 €/W_P (2013).

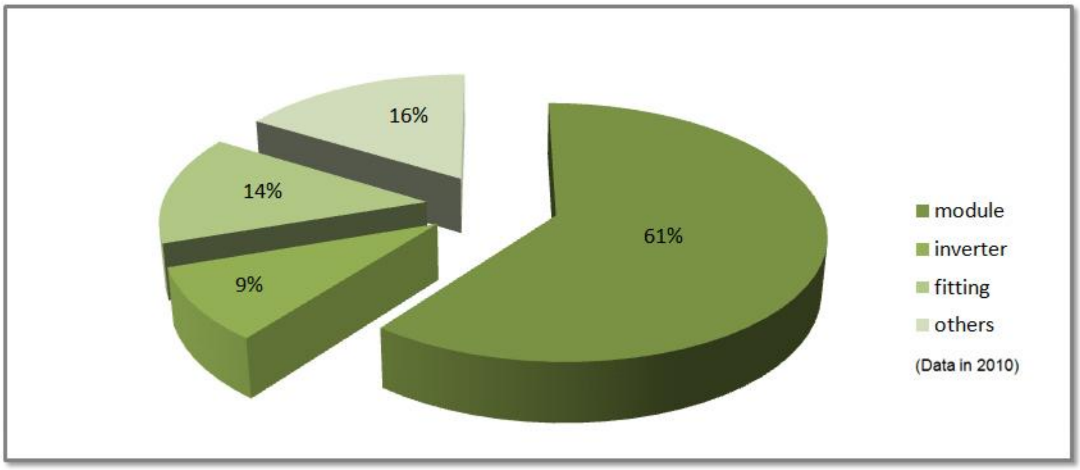


Fig 4.3.3 Investment for PV system

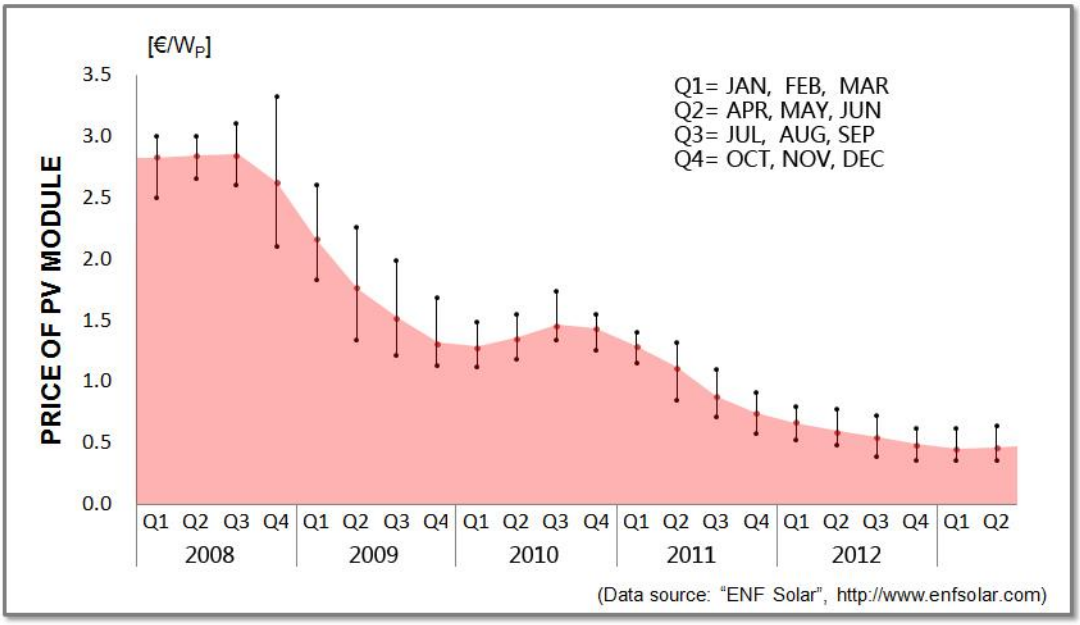


Fig 4.3.4 Price of PV module

Investment for PV system is strongly reduced because of the lower module price. When the price of PV module is 0.46 €/W_P, investment for PV system could decrease from 2600 €/kW_P (in 2010) to 1500 €/kW_P (2013).

Compared with other systems (as Chapter 4.2.3), when investment for PV system is cheap (1500€/kW$_P$ in 2013), system-D will have economic advantage even without government financial support for PV system (Fig 4.3.5) in the future.

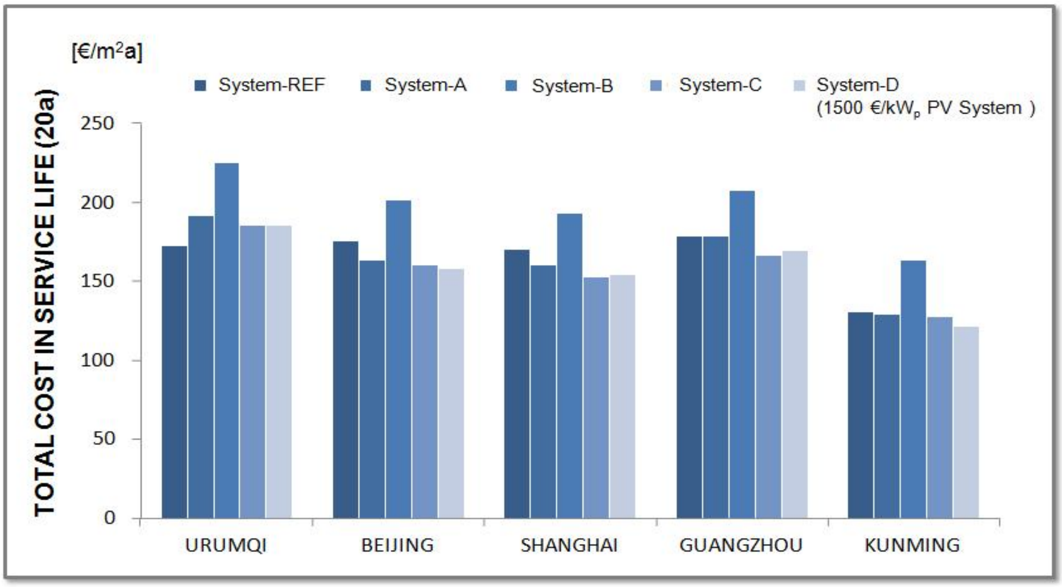


Fig 4.3.5 Total cost for various systems in service life (20a)

4.3.3. Energy supply in the future

In the future, Chinese district heating is estimated to be supplied by CHP (combined heat and power generation).Total primary energy demand of system-REF, A, B, C and D (as Chapter 4.2.3) could be shown as Fig 4.3.6.

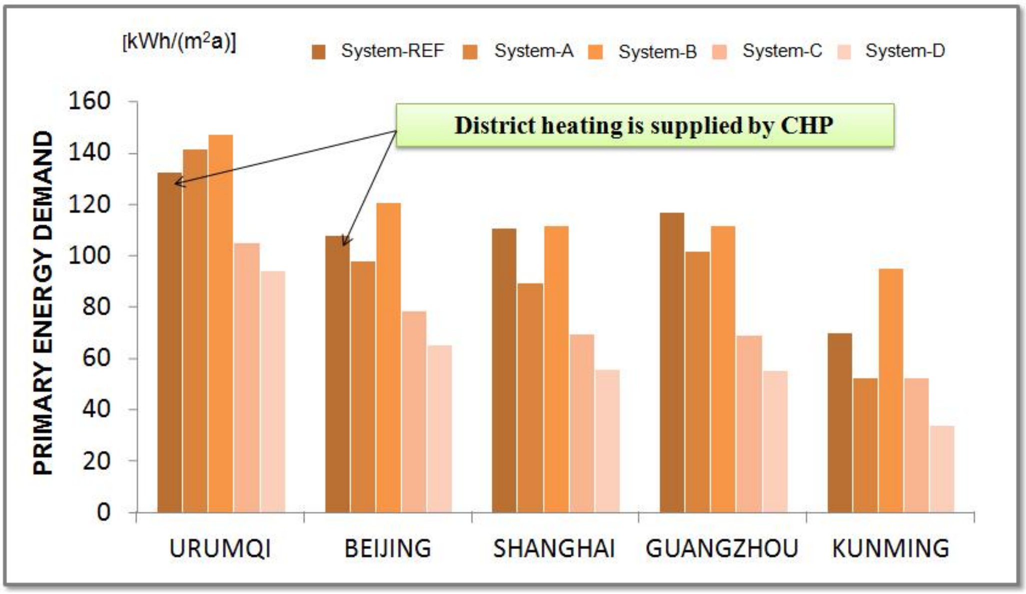


Fig 4.3.6 Primary energy demand in the future

Compared with developed countries (for example Germany), the fuel price in China is still lower (Fig 4.3.7). For example, the electricity price in China is a factor 3 lower than that in Germany. It goes up quickly both in China and in Germany. However, it could be expected, the energy price in China will catch up developed countries in the future.

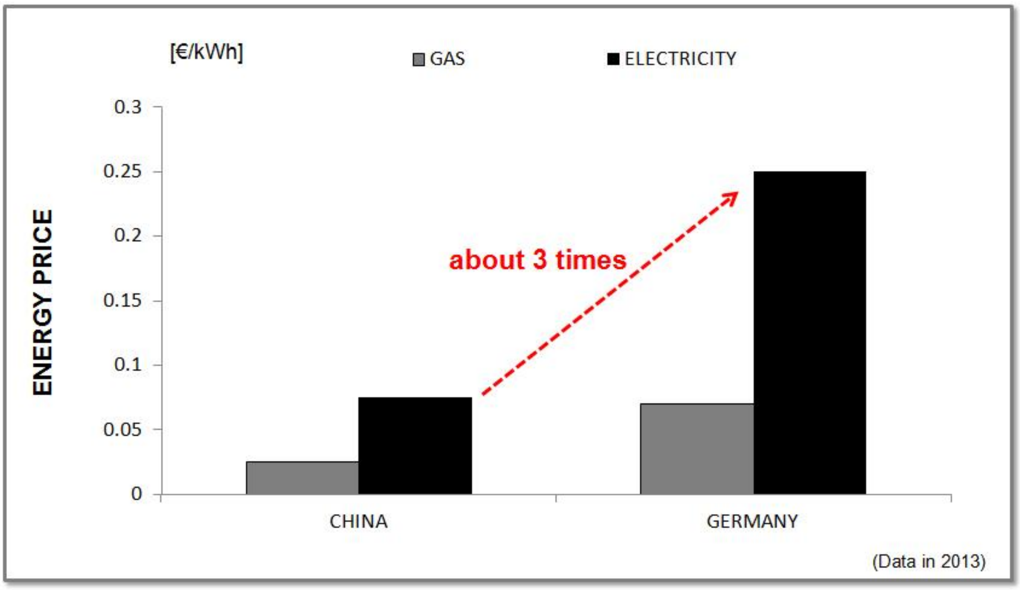


Fig 4.3.7 Energy price in China and Germany

When energy price goes up to the same level as developed countries (Germany), the total cost in service life (20a) could be shown as Fig 4.3.8.

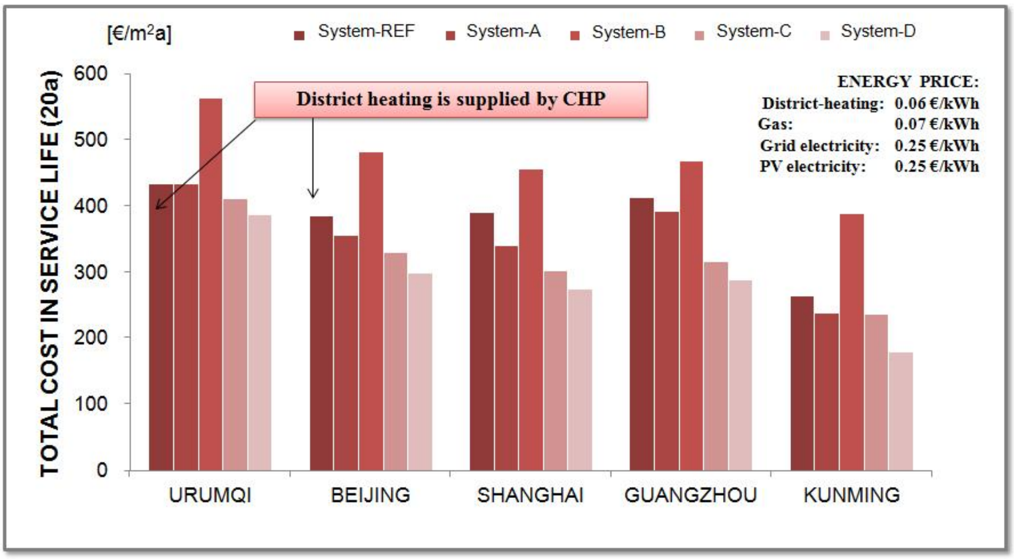


Fig 4.3.8 Total cost in service life (future)

According to Fig 4.3.6 and Fig 4.3.8, system-D has the lowest energy demand and the lowest cost. The combination of GCHP and PV system is proved to be the most suitable building service system for Chinese energy efficient multi-story residential buildings in the future.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The objective of this research is finding comprehensive concepts of energy efficient multi-story residential building in various climate zones in China. Building envelope and building service systems are separately discussed. Five cities (Urumqi, Beijing, Shanghai, Guangzhou, Kunming) are chosen as representative city in each climate zone (severe cold, cold, hot summer and cold winter, hot summer and warm winter, warm zone, Chapter 2.1). In Chapter 4.1, optimal building envelope is discussed. According to cost calculation and energy simulation, optimal thickness of thermal insulation, optimal window-to-wall ratio (WWR) and glazing types are suggested for Chinese energy efficient multi-story residential buildings. In Chapter 4.2, four types of building service systems (system-A, B, C, D) are examined. Primary energy demand of overall system is discussed, including domestic hot water, space heating, space cooling, lighting and appliances. Total cost in service life (20a) is also considered. In Chapter 4.3, challenges and opportunities for Chinese energy efficient multi-story residential buildings in the future are predicted. Conclusions of this research are listed as follow.

About Building envelope:

- ✧ Considering recent energy supply system and energy price, optimal thicknesses of EPS for external wall are 134 up to 241mm in Urumqi, Beijing, Shanghai, Guangzhou and Kunming.
- ✧ Optimal thermal insulation could reduce energy demand and save money in service life (30a).
- ✧ In cold cities (Urumqi and Beijing), high window-to-wall ratio (WWR 50% up to 90%) is more suitable for southern windows. Window area on northern wall should be small. With the consideration of day lighting, WWR of northern windows is suggested to be 20% up to 40%.
- ✧ In Guangzhou and Kunming, where cooling demand is dominant, small WWR (20% up to 40%) is suggested for both northern and southern windows.
- ✧ In Shanghai, large window area on southern wall is able to reduce heating demand. Shading system should be integrated for southern windows in order to get rid of high cooling demand in cooling period.
- ✧ Double Low-E glazing (D-LOE) is the most suitable glazing type in cold cities (Urumqi and Beijing). Double reflect glazing (D-REF) is the best choice in hot cities (Guangzhou) and warm cities (Kunming).
- ✧ In Shanghai, which locates in “Hot summer and cold winter zone”, double Low-E glazing and double reflect glazing are both suitable for southern windows. Double Low-E glazing is better than double reflect glazing when WWR < 50%. Double Low-E glazing is also the best choice for northern windows in Shanghai.

About Building heating and cooling system:

- ✧ Using solar assisted thermal system instead of reference systems (Chapter 2.2.2) to supply domestic hot water and space heating could reduce primary energy demand. It could also save money in most cities, except in Urumqi.

- ✧ The combination of “Ground-coupled heat pump system (GCHP)” and “Photovoltaic (PV) system” could save the most primary energy demand. However, its investment is the highest among these systems (Chapter 4.2.3.1). The combination of “Ground-coupled heat pump system (GCHP)” (for space heating/cooling) and “air-source heat pump system” (for domestic hot water) has more economic advantages.
- ✧ Considering the government financial support for PV systems, the combination of Ground-coupled heat pump system (GCHP) and PV system could achieve the lowest total cost in service life (20a).
- ✧ Combined heat and power generation (CHP) is a favorable choice for district-heating in the future. Total primary energy demand could be 30% and 11% reduced in Urumqi and Beijing, respectively.
- ✧ Investment for PV system decreases quickly in recent years. Government financial support for PV integrated buildings will be not necessary any more in the future.

5.2. Recommendation

The following part contains recommendations for energy efficient multi-story residential buildings in various investigated cities (climate zones). These recommendations could be applied for other city, which locates in the same climate zone.

Urumqi (severe cold zone):

- ✧ Considering recent energy supply system and energy price, the thicknesses of EPS for external wall in Urumqi should be approximately 200 mm.
- ✧ High WWR (50% up to 90%) is suitable for southern windows, while small WWR (20% up to 40%) is suitable for northern windows. Double Low-E glazing should be widely used.
- ✧ District-heating should be supplied by combined heat and power generation (CHP).
- ✧ The combination of Ground-coupled heat pump system (GCHP) and Photovoltaic system (PV) should be encouraged.

Beijing (cold zone):

- ✧ Considering recent energy supply system and energy price, the thicknesses of EPS for external wall in Beijing should be about 240 mm.
- ✧ High WWR (50% up to 90%) is suitable for southern windows, while small WWR (20% up to 40%) is suitable for northern windows. Double Low-E glazing should be widely used.
- ✧ District-heating should be supplied by combined heat and power generation (CHP).
- ✧ The combination of Ground-coupled heat pump system (GCHP) and Photovoltaic system (PV) should be encouraged.

Shanghai (Hot summer and cold winter zone)

- ✧ Considering recent energy supply system and energy price, the thicknesses of EPS for external wall in Shanghai should be about 230 mm.
- ✧ Large windows (WWR 50% up to 90%) with shading system should be designed on southern wall. Double Low-E glazing (D-LOE) and double reflect glazing (D-REF) are both suitable for windows.
- ✧ The combination of Ground-coupled heat pump system (GCHP) and Photovoltaic system (PV) should be encouraged.

Guangzhou (Hot summer and warm winter zone)

- ✧ Considering recent energy supply system and energy price, the thicknesses of EPS for external wall in Guangzhou should be approximately 135 mm.
- ✧ Small windows (WWR 20% up to 40%) are suggested for both northern and southern windows.
- ✧ Double reflect glazing (D-REF) is the most suitable glazing type.
- ✧ The combination of Ground-coupled heat pump system (GCHP) and Photovoltaic system (PV) should be encouraged.

Kunming (warm zone)

- ✧ Considering recent energy supply system and energy price, the thicknesses of EPS for external wall in Kunming should be about 185 mm.
- ✧ Small windows (WWR 20% up to 40%) are suggested for both northern and southern windows.
- ✧ Double reflect glazing (D-REF) is the most suitable glazing type.
- ✧ The combination of Ground-coupled heat pump system (GCHP) and Photovoltaic system (PV) should be encouraged.

Chapter 6

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